2021

Quantification of Climate Variability and Extreme Events in the Great Plains

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QUANTIFICATION OF CLIMATE VARIABILITY AND EXTREME EVENTS IN THE GREAT PLAINS

BY

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A dissertation submitted in partial fulfillment of the requirements for the

Doctor of Philosophy

Major in Civil Engineering

South Dakota State University

2021

DISSERTATION ACCEPTANCE PAGE

Angelinah Rasoeu

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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My little angel Wisdom, when I started this Ph.D., you were only 2 years old. Now you are a big girl, almost 7 years old. We have been through so much together and I could not have done it without you in my life. I am so grateful that I went through this with you. Thank you for your support, always forcing me to go to the gym or do Gonoodles with you so I could stay healthy and monitoring my diet to make sure I eat healthy food. Thank you for giving me hugs and kisses when I needed them and listening to my struggles even when you did not understand them, but you always had the sweetest thing to say and always pushing me to finish so you could call me a doctor. Coming home to you gave me so much joy and strength and coming to the office with you on weekends was such a motivation and gave me satisfaction that we could still spend time together when I am working. To my surprise it was your favorite thing to do over playing. Seeing the joy on your face when you say you want to be an engineer like mommy and seeing your joy when you call yourself a computer engineer gave me so much motivation to work hard and be a good role model for you. You are my angel, and I am so grateful for you.

To my dearest grandparents, I am sure you are very proud of me from heaven. You raised me to be a strong and kind woman. You sacrificed so much for me to have a chance in life. Thank you for instilling in me to value education. Even though you left me too soon and did not get to see me graduate from college and now Ph.D., your encouragements and cheering when I was young were very inspirational to me. Your words kept me going and took me through tough times and it was as if I hear you talk. Thank you for being my heroes and laying out a strong foundation for me. I could not have dreamed of studying overseas and getting a Ph.D. You were also telling me I would

be very educated and go to study overseas even though at the time, as a little child, I did not know anything about education and overseas. This dissertation is to honor you.

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to my remarkable advisor Dr. Suzette Burckhard for her tireless guidance and support to make sure I achieve my education goals. With her patience, rich knowledge, and skills, she made my Ph.D. journey workable. In a world of academia where parents, especially moms, who have the responsibility of raising families, it has never been easy for some parents to pursue their education while raising a family. It is even extremely difficult for single moms like me who do not have a helping hand at home. Dr. Burckhard made it workable for my situation and words cannot describe how grateful I am for her. Many times, I had worried and questioned if I would make it but with her kindness, encouragements, and patience, she gave me hope every time when I felt overwhelmed, and that was the only thing that I needed to persevere. Words cannot describe how grateful I am to have been under her mentorship.

I would also like to thank my committee members, Dr. Christopher Schmit, and Dr. Bruce Millett for their guidance and tireless support and my graduate representative Dr. Keith Underwood for his guidance and support. My Ph.D. would not be done without them. My gratitude also goes to Civil and Environmental Engineering Department and staff for creating a convenient learning environment and providing resources to help me succeed. My gratitude to my colleagues in the graduate office, Abdoul, Philip, and Ali for their support and intellectual discussions.

I thank Fulbright which initially brought me to U.S. for graduate school, for giving me a life changing opportunity to study abroad and funding my MS studies. The findings presented in this dissertation are upon work funded by AAUW, PEO, and

Department of Civil and Environmental Engineering. I also thank South Dakota State University for the education and great experience I gained during my studies here at SDSU.

Finally, I thank my family and friends, my daughter Wisdom for being such a great motivation and support, Cody, for being my best friend and a good boyfriend and providing a shoulder to learn on and Molefi for being a genuine friend during all my degrees, your constant support even though you were thousands of miles away, you always made sure you constantly check on my progress. It is through your support and encouragements that I was able to complete my studies.

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ABBREVIATIONS

BSR	Big Sioux River
cfs	cubic feet per second
in.	inches
ft	feet
precip	precipitation
stddev	standard deviation
gage	gauge

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ABSTRACT

QUANTIFICATION OF CLIMATE VARIABILITY AND EXTREME EVENTS IN THE GREAT PLAINS

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Climate variability and extreme events continue to worsen resulting in significant impacts to society and the environment. Quantifying precipitation variability, streamflow, and extreme events at local scale is crucial for local planning and management due to spatial and temporal precipitation variability which influences streamflow and thus, water resources. This study uses statistical tools to analyze 1895-2019 (125 years) of historical precipitation data to examine how long-term precipitation varies annually, seasonally, and monthly, and create climate classifications. The results show that annual precipitation is increasing linearly over time ranging from 13.2 in (1976) to 43.1 in (2010) and 5 climate classes were created. On average, precipitation is highest in June and Spring and lowest in January and Winter. The coefficient of variation (CV) shows that months and seasons with low precipitation have highly variable precipitation and vice versa.

Extremes result in major damages and economic impact due to floods and droughts. To gain an in-depth knowledge, this study uses statistical methods to quantify Very Wet and Very Dry climate classifications identified from 1895-2019 precipitation data. Very Wet climate shows an annual precipitation and snowfall increase from long-term average of up to 70% and 116%, respectively, while Very Dry climate shows an annual precipitation decrease of up to 49% and snowfall decrease of up to 73% .

However, the number of days with precipitation are similar for both Very Wet and Very Dry, precipitation intensity and magnitude influence total. Very Wet has highest precipitation in Summer and July while Very Dry has highest in Spring and June and both have highest snowfall in Winter.

This study uses statistical methods to analyze how long-term precipitation relates to long-term flows, analyzed peak flows, and flood events. The results show higher Spring and annual correlation between precipitation and streamflow. The watershed experiences minor to major floods due to snowmelt in Winter and Spring and rainfall in Spring and Summer. The results show a highly variable and less predictable climate, and floods occur even during Very Dry climate due to extreme events and accumulation of groundwater levels from previous years or seasons. The findings show the need to incorporate climate variability at local scale in water resources management.

Chapter 1: Introduction

1.1.Background

Climate variability and extreme climate events continue to worsen resulting in significant impacts on society (NOAA, 2020; UN, 2002). The increase in frequent and severe occurrences of storms, floods, and droughts result in economic loss and destroys lives, crops, properties, infrastructure, and the environment (NOAA, 2020; UN, 2002). Climate variability and extremes also affect water availability needed for domestic, industrial, agricultural, and recreation uses. The long held stationary assumption that precipitation would not change significantly over time is no longer valid and understanding climate variability is crucial now more than ever to protect the society and the environment.

According to UNDRR, flooding is the leading water-related disaster with greatest damage and effect worldwide (UNDRR, 2002). United Nations reported that floods affected over 17 million people in 2002 in over 80 countries with about 3000 deaths and thirty billion US dollars' worth of property damage and 8 million square kilometers affected (UN, 2002). From 1998 to 2017, losses due to extreme weather events increased 151 percent compared to the previous 20 years. The U.S. had 273 weather and climate disaster events since 1980, with damage or cost of over $1.790 trillion and 14,223 deaths (NOAA, 2020). In the last 5 years, there were 69 events with $535.6B damage cost and 3862 deaths while in the last 3 years there were 44 events and 460.4B with 3569 deaths (NOAA, 2020). According to NOAA (2020), 2015-2020 were continuous years with 10 or more billion-dollar weather and climate disaster events that impacted United States. In U.S., The upper Mississippi and Missouri river experience record flooding due to early

snow melt and heavy spring rain and late spring snowfall and flood is elevated in central and southern U.S. as water flows downstream (Floodlist, 2019).

Severe droughts are continuing to have serious impacts on some parts of the world leading to starvation and dependence on food aid. Severe drought affects over 37% of United States with the longest time span in southeastern states (UNDRR, 2002). Some countries experience all extremes simultaneously such as the Unites States (UN, 2002).

The literature shows that human-induced global warming increase temperatures (Bates et al., 2008; EPA, 1998; IPCC, 2007, 2014; Karl et al., 2009; Karl & Trenberth, 2003) causing high atmospheric vapor, resulting in intense and altered precipitation patterns (C2ES, 2020; Cheng & AghaKouchak, 2014). Historical data and projections show that the extreme events are expected to be more frequent and severe, and the magnitude, timing, and patterns of precipitation is projected to change and affect runoff (Bates et al., 2008; EPA, 2016; IPCC, 2007, 2014). The effect of severe and altered precipitation on hydrologic systems include early spring snow melt causing early spring peak discharge, increase in runoff, and water quality issues of warming rivers and lakes (IPCC, 2007). The effects can be worse in urban areas where there is high level of imperviousness and spatial variability in land use, and hydrological response is sensitive to small scale rainfall variability in both space and time (Cristiano et al., 2017). Therefore, analyzing precipitation, both rainfall and snowfall, and streamflow and their timing could help in assessing floods, droughts, storm sewer designs, runoff forecasting for developing hydropower and irrigation and water availability and management.

Precipitation is a major element in the hydrologic cycle (continuous processes by which water circulates from earth to the atmosphere and back) and its extreme occurrences result in floods and droughts. Extreme precipitation events occur in most parts of the world resulting in floods, droughts, water quality issues, which destroy lives and properties (Karl et al., 2009; Tramblay et al., 2013). The current increasing climate change and variability concerns require accurate information on the spatial and temporal variability of precipitation.

1.1.1. Effects of precipitation on Infrastructure design

As extreme precipitation events are becoming more frequent and severe, it is critical to update current infrastructure designs which are based on the stationary precipitation assumption which means precipitation does not change over time. Current infrastructure is designed using precipitation Intensity-Duration-Frequency (IDF) curves which assumes stationary precipitation. The study done in five states in U.S. indicates that using current IDF curves, which assume stationary precipitation, extreme precipitation may be underestimated by 60 % under non-stationary (Cheng & AghaKouchak, 2014). Non-stationary means precipitation will significantly change over time. They also found that the shorter the duration of the storm, the larger the underestimation (the difference between non-stationary and stationary extremes). Due to climate change and variability which result in non-stationarity, the concept of probability of exceedances and return period may no longer be valid (Khaliq et al., 2006; Milly et al., 2008; Tramblay et al., 2013; Westra & Sisson, 2011). Milly et al. (2008) indicated that stationarity is dead and cannot be revived, and we need to find new approaches to deal with non-stationary precipitation.

Urban and industrial areas which have an increased imperviousness due to development, experience high runoff, higher peak flows, and early time to peak during storm events. The capacity of drainage systems designed to drain runoff can be exceeded during extreme storm events and this can cause flooding (Qin et al., 2013). A study in Maryland showed an increase of 30% in 100-year flood in non-stationary flood frequency analysis method that account for urbanization and climate change for 2100 design year (Gilroy & McCuen, 2012). Hence the need to improve existing drainage systems to account for extreme storm events.

1.1.2. Effects of precipitation on hydrologic modeling

The limitations of hydrological measurements techniques are why we model rainfall-runoff processes of hydrology. In hydrologic modeling, rainfall is mostly the main input in rainfall-runoff modeling, and this requires real rainfall representation in time and space (Cristiano et al., 2017). Therefore, it is critical to evaluate rainfall variability to accurately represent precipitation in modeling (Faurès et al., 1995). Cristiano et al. (2017) stated that the availability and quality of rainfall input data is needed to balance model complexity and resolution. Another author indicated that variability is more important than averages, thus, climate models need to be designed to detect changes in climate variability (Katz & Brown, 1992). Therefore, the analysis of climate variability is necessary to help water planners, managers, and decision makers to know what kind of adaptations including changes in infrastructure designs are needed to protect the public (Cheng & AghaKouchak, 2014).

1.1.3. Methods used for climate variability analysis.

Climate studies have mainly focused on climate extremes at global scale or regional scale however, assessing climate variability and extremes at local scale are needed to quantify climate patterns and intensity to manage local water resources as opposed to regional analysis (Priya et al., 2017). The studies done around the world differ due to different approaches, location of the study area, size of the area, and the climate variable being investigated. Most studies have evaluated either precipitation, precipitation and temperature, temperature, or streamflow trends to investigate climate variability or non-stationarity (Cheng & AghaKouchak, 2014; Damberg & AghaKouchak, 2013; Douglas et al., 2000; Elagib, 2010; Mosase, 2018; Sagero et al., 2018).

The commonly used methods are coefficient of variation (CV) described in the methodology section which is used in hydrology as a measure of potential seasonal and interannual fluctuations in water availability for regions (Water systems Analysis Group, n.d.) and Mann Kendall (MK) trend test or modified Mann-Kendall trend test which is a non-parametric method developed for trend analysis in time series data (Hamed & Rao, 1998) and this uses slope factor to detect an increase or decrease in trend.

Studies done in Kenya, and Southern Africa, used both MK test and CV to investigate rainfall variability (Mosase, 2018; Sagero et al., 2018). Studies in south Korea, United States, Canada, and Sudan, used MK test to evaluate trends in precipitation, floods, and low flow (Azam et al., 2018; Douglas et al., 2000; Elagib, 2010; Priya et al., 2017; Zadeh et al., 2020). The study done in Sudan used CV to investigate

temperature trends (Elagib, 2010). The results of all these studies generally show spatial variability within a study location and across study locations.

Other studies used different approaches. In China, the study on variations of precipitation characteristics used linear regression to calculate trend rate and showed non-significant increasing annual precipitation trend, however, the days of higher (10-25 mm) precipitation increased (Iqbal et al., 2018). Another study used a water balance equation to investigate spatial patterns and recent trends in climate of tropical rainforest regions (Malhi & Wright, 2004). The study done in Kenya used the MK test for rainfall trends and Surfer for spatial distribution to investigate the possible effect of urbanization on rainfall variability (Ongoma et al., 2015).

The United States Geological Survey (USGS) applied parametric methodology, which involves creating climate scenarios, to evaluate lake levels (Niehus et al., 1999). This approach was applied in master’s thesis work to evaluate climate variability in northeastern South Dakota (Amatya, 2011; Basnet, 2011; Kshatriya, 2018; Ruppert, 2019). This approach could be effective in analyzing climate variability and identifying extreme climate; however, the master’s thesis applied the methodology to a short range of data and mostly using an 8-year cycle, which is thought to be the South Dakota climate cycle. This approach allows for analyzing climate variability and identifying and understanding extremes and can be generally applied to any location to evaluate any climate parameter variability such as temperature and others.

1.2.Problem statement

It is evident from the literature that analyzing precipitation variability, streamflow and extremes is crucial as the effects on the public, economy, and water resources are inevitable. Local scale analysis is necessary for local planning and management and a simple but robust method is necessary to evaluate precipitation variability. The climate studies have mainly focused on the mean and extremes on the global or regional scale. However, quantifying climate variability at location scale is crucial to help water managers and planners to make location appropriate decisions including design of storm infrastructure to protect the public.

Currently there is no clear method used to quantify climate variability, and MK trend analysis is a well-documented commonly used approach. However, trend analysis does not provide much useful information about climate variability to help in decision making since it only investigates whether there is an increasing or decreasing trend in climate data. Since MK test is non-parametric, it does not consider normality of data, so it is weak compared to parametric tests which are more powerful and require normality and perform well with skewed data (Serinaldi et al., 2018). Serinaldi et al. (2018) also argued that trend null hypothesis used in MK test is uninformative and to infer non-stationary, it assumes a prior additional information on underlying stochastic process thus, the outcomes of null hypothesis testing do not support non-stationary frequency analysis and modeling. The USGS parametric methodology which involves creating climate scenarios could be effective in quantifying climate variability and needs to be advanced with a long-term data.

Since precipitation is influenced by general atmospheric circulation, closeness to large water bodies, and topography, it can vary within a short distance (Taylor, 2019). It is important to study precipitation variability on a local scale to understand long term annual, seasonal, and monthly precipitation variability and patterns, and identify and quantify extreme events for a specific area. This is important for local planning to help decision makers, water managers and planners to make necessary location specific plans and adjustments to protect the public such as improving local infrastructure design as opposed to global and regional analysis. The local analysis can then be used to develop regional analysis.

1.3.Objectives of the study

The purpose of this study is to use statistical methods to quantify long-term climate variability at local scale to understand long-term annual, seasonal, and monthly climate variability and extremes. The specific objectives are to:

1. Quantify long-term precipitation variability using historical precipitation. Specific goals are:
    a. Perform monthly, seasonal, and annual analysis to quantify precipitation variability.
    b. Create climate classifications and quantify precipitation in each climate classification.
2. Quantify inter and intra annual, seasonal, and monthly extreme precipitation variability (Very Wet and Very Dry Climate Classifications) to quantify their severity and identify patterns or lack of. Specific goals are:

   a. Quantify inter and intra annual, seasonal, and monthly extreme precipitation (precipitation, snowfall, and their number of days) for Very Wet and Very Dry climates.
   b. Compare Very Wet and Very Dry climate

3. Quantify long-term extreme precipitation and extreme flow events relationship. Specific goals are:

   a. Quantify daily, seasonal, and annual correlation between streamflow and precipitation.
   b. Assess peak flow events, flood events, and climate variability impacts.

1.4.Significance of the study

This study is intended to improve the state of knowledge in climate variability analysis at local scale and the methods developed here can be incorporated in climate variability evaluation and water management planning and decision making to protect the public. This study adds a simple but useful methodology in analyzing climate variability, understanding extremes, streamflow and precipitation relationship, and floods analysis at the local scale. Floods and droughts that have major impact on the public and economy. Although the methods here were applied to eastern South Dakota, this approach can generally be applied to other locations, and other climate parameters. The outputs can be used with climate models to predict future climate, and this can help water managers and planners in early planning.

1.5.Organization of the Dissertation

The dissertation is organized in six chapters. Chapter 1 is the background of the study which includes, introduction, literature review, problem statement, and objectives of the dissertation. Chapter 2 quantifies long-term annual, seasonal, and monthly precipitation variability. Chapter 3 analyzes and quantifies extreme precipitation events, and Chapter 4 quantifies long-term precipitation and streamflow relationship and quantify extremes, and Chapter 5 summarizes the findings and conclusions, and Chapter 6 provides recommendations of further research. Chapter 2 to 4 are written in manuscripts format for publication in peer reviewed journals, therefore, some information including references may be repeated in the dissertation.

Chapter 2: Quantifying Long-Term Precipitation Variability 1895-2019.

Abstract

Climate variability is an important issue due to its socioeconomic impacts due to floods and droughts. The literature is mainly focused on the extreme events, however the variability in climate creates a less predictable climate and inability to plan for extremes. It is critical to have an in-depth understanding of climate variability at local scale to incorporate in water management, policy and decision making. However, the methodology to quantify climate variability is lacking and the focus has mainly been on trend analysis and extremes. This study applies a robust methodology to quantify climate variability. The methodology was applied to long-term precipitation data from 1895-2019 (125 years) from Sioux Falls Foss Field station. Precipitation was analyzed as cumulative and for climate classifications. Precipitation was classified as Very Wet, Wet, Average, Dry and Very Dry climate. The results show annual, seasonal, and monthly variability, with 2010 having highest precipitation with 43.1 in, and 1976 having lowest with 13.2 in. The precipitation deviation from the mean is an increase of 48% in Very Wet and 21% in Wet and decrease of 36% in Very Dry and 19% in Dry climate. On average, Spring season and the month of June have highest precipitation with 7 and 9.5 in increases from averages, respectively and Winter, and January have lowest precipitation with 3.9 and 1.6 in decrease from the averages, respectively. Annual coefficient of variations (CVs) is 21% indicating less overall annual variability from the average precipitation. Very Wet and Very Dy have higher CVs. Generally, seasons, and months with low precipitation have high CVs, meaning highly variable precipitation from the average, and those with

high precipitation have low CVs, meaning less variability. The precipitation shows a slide linear increase over time.

2.1. Introduction

The frequent occurrences and worsening of extreme climate events call for the need to quantify climate variability. The increase in climate variability means less predictability in climate due to large monthly, seasonal and year to year fluctuations. Whether natural or anthropogenic, climate variability result in storms, floods, droughts and others that result in significant socioeconomic impacts such as economic loss, loss of lives, and crops, and damage of properties, infrastructure, and the environment (NOAA, 2020; UN, 2002). Some countries experience all extremes simultaneously including United States with 10 or more-billion-dollar climate disasters such as floods, storms, hurricanes, droughts, and others. (Floodlist, 2019; NOAA, 2020; UN, 2002; UNDRR, 2002). Climate variability needs to be incorporated in climate and water management planning to assist with adaptation and coping strategies to long-term climate variability impacts (Bates et al., 2008).

Climate variability is defined as “variations or deviations from the mean state of climate of temporal variations of the atmosphere-ocean system around a mean state measure over a long period of time”(Institute of Medicine, 2008). The in-depth understanding of variability and extremes aid to develop coping strategies (Heim, 2015) such as building infrastructure that can withstand the heaviest precipitation and withstand severe drought.

The literature shows that human-induced global warming increases temperatures (EPA, 1998; IPCC, 2007, 2014; Karl et al., 2009; Karl & Trenberth, 2003) causing high

atmospheric vapor, resulting in intense and altered precipitation patterns (C2ES, 2020; Cheng & AghaKouchak, 2014). The effect of severe and altered precipitation on hydrologic systems include early Spring snow melt causing early Spring peak discharge, increase in runoff, and water quality issues of warming rivers and lakes (IPCC, 2007). Severe and altered precipitation result in floods and droughts leading to water quality issues, loss of lives, destruction of properties, infrastructure, and economy. The spatial and temporal variability of precipitation is a challenge for local water management and planning. The effects can be worse in urban areas where there is high level of imperviousness and spatial variability in land use, and hydrological response is sensitive to small- scale rainfall variability in both space and time (Cristiano et al., 2017).

Analyzing precipitation to evaluate climate variability at local scale is important for relevance to decision making (Bates et al., 2008). It is critical to evaluate climate variability and extremes to have an in-depth understanding of how climate varies and quantify variability, extremes, and their severity. This would in turn aid in making necessary adjustments such as updating designs and making predictions which are based on historical records and need to be made earlier before extreme happens.

The literature shows that the long-used assumption that climate is stationary, meaning it would not change over time is no longer valid, and the concept of return period and probability of exceedances may no longer be valid under current worsening variable climate (Khaliq et al., 2006; Milly et al., 2008; Tramblay et al., 2013; Westra & Sisson, 2011). This means designs which are based on current Intensity-Duration-Frequency (IDF) curves, which assume stationary precipitation, could underestimate extreme precipitation by 60 % under non-stationary precipitation (Cheng & AghaKouchak, 2014).

In hydrologic modeling, it is also critical to evaluate rainfall variability to accurately represent precipitation in modeling (Cristiano et al., 2017; Faurès et al., 1995).

The climate studies have mainly focused on mean and extremes on global or regional scale. However, climate variability studies on a local scale are needed to help water managers and planners to make location appropriate decisions including design of storm infrastructure to protect the public. There is no clear method for quantifying climate variability. Most studies investigated trends in precipitation, temperature, and streamflow to investigate climate variability or non-stationary (Cheng & AghaKouchak, 2014; Damberg & AghaKouchak, 2013; Douglas et al., 2000; Elagib, 2010; Mosase, 2018; Sagero et al., 2018). Studies used non-parametric Mann Kendall (MK) trend test (Hamed & Rao, 1998) to investigate climate variability (Azam et al., 2018; Douglas et al., 2000; Elagib, 2010; Priya et al., 2017; Zadeh et al., 2020), some used both the MK test and CV (Mosase, 2018; Sagero et al., 2018), some only CV (Elagib, 2010). Some used linear regression (Iqbal et al., 2018) and water balance equation for trend analysis (Malhi & Wright, 2004). However, trend analysis, though good does not provide much useful information about climate variability to help in decision making since it only investigates whether there is an increasing or decreasing trend in climate data. Since MK test is non-parametric, it does not consider normality of data, so it is weak compared to parametric tests which are more powerful and require normality and perform well with skewed data (Serinaldi et al., 2018). Serinaldi et al. (2018) also argued that trend null hypothesis used in MK test is uninformative and to infer non-stationary, it assumes a prior additional information on underlying stochastic process and the outcomes of null hypothesis testing do not support non-stationary frequency analysis and modeling.

The United States Geological Survey (USGS) applied parametric methodology, which involves creating climate scenarios, to evaluate lake levels (Niehus et al., 1999). The USGS methodology was applied in master's thesis work to evaluate climate variability in northeastern South Dakota (Amatya, 2011; Basnet, 2011; Kshatriya, 2018; Ruppert, 2019). This methodology could be effective in analyzing climate variability and identify extreme climate; however, these master's thesis studies applied the methodology to a short range of data and mostly using 8-year cycle, which is thought to be South Dakota climate cycle.

This study aims to apply USGS methodology to 125 years of data to evaluate climate variability to quantify long-term annual, seasonal, and monthly precipitation variability at local scale. This methodology allows for analyzing climate variability and identifying extremes. This methodology can be generally applied to any location to evaluate any climate parameter variability such as temperature.

2.2. Methodology

2.2.1. Study area

The study was performed in Sioux Falls, the biggest city in South Dakota, United States of America. Sioux Falls is in Minnehaha County and extends into Lincoln County (Figure 2.1). Sioux Falls is in the Big Sioux River Valley in southeastern South Dakota, United States (Figure 2.2). It is located at 43.55^{o}N, 96.73^{o}W and lies 1421 feet above sea level. There is a diversion canal along the Big Sioux River and Skunk Creek to reduce flooding at the airport during high flows. The location of the weather station used in this study is at the airport FSO 397667 (Coop) located at 43.5778 degrees, -96.7539 degrees in between the Big Sioux River and the diversion canal (Figure 2.2). According to U.S.

Census Bureau (USCB, 2018) Sioux Falls covers about 78.04 square miles of which 77.5 square miles is land and 0.53 square miles is water. The population was 183,793 as of 2019 census. The land uses are residential and commercial areas, pastures, croplands, hayfields, forests, and farmlands (Chuang et al., 2011).

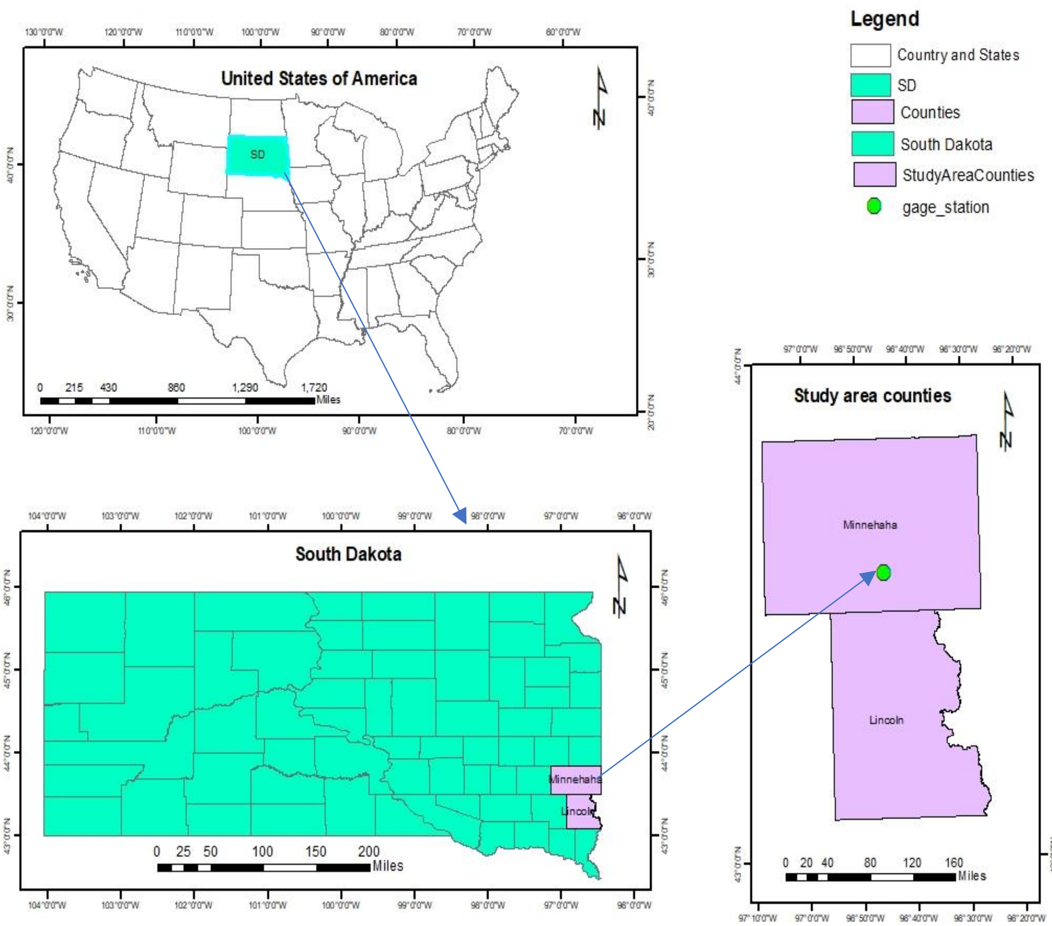


Figure 2.1. Location of study area in the United States of America, the state of South Dakota, counties, and the location of the precipitation gauge.

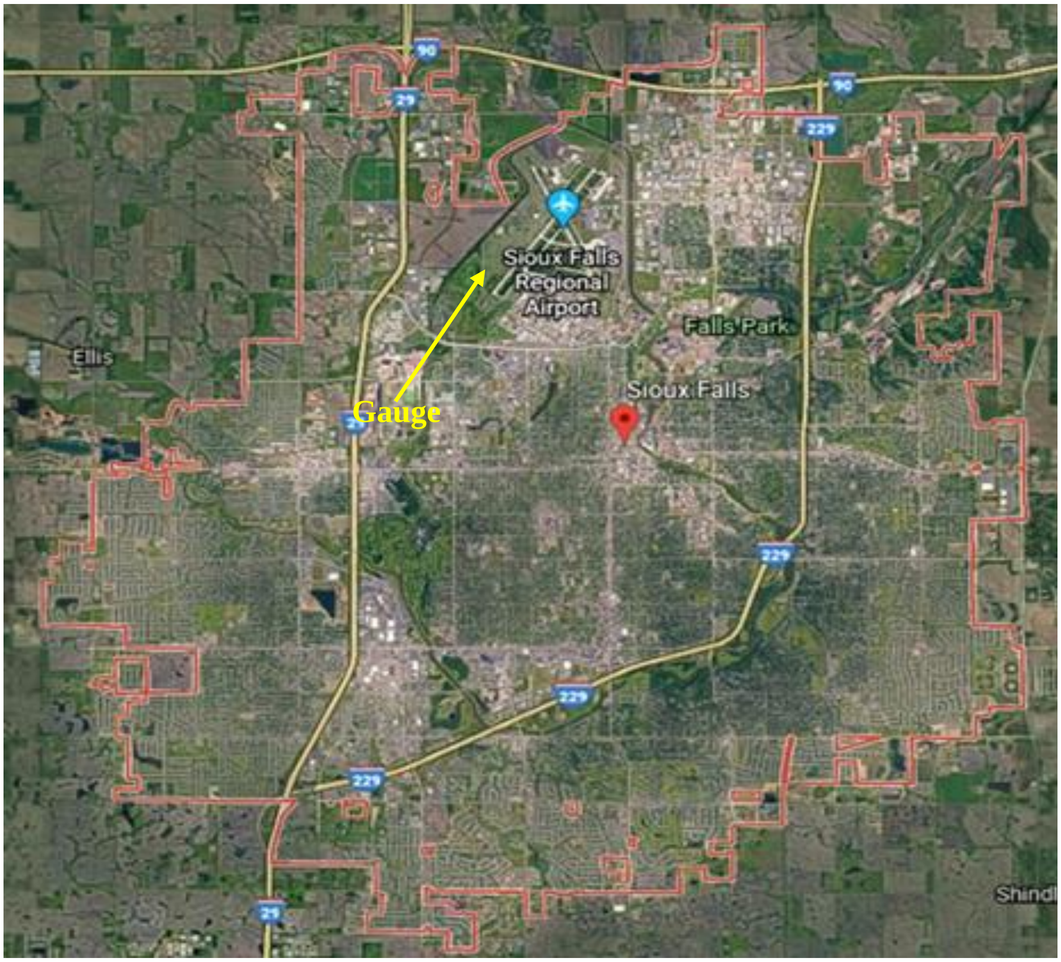


Figure 2.2. Aerial photo of the City of Sioux Falls boundary and location of gauge.

The annual average temperature is 45.1 Fahrenheit (^{o}F) and averages with 14 ^{o}F in January, and 73 ^{o}F in July. The average annual precipitation is 24.69 inches of rain and 38.1 inches in snow.

Sioux Falls is under hydrologic subregion A which is described as Minnesota-Red River Lowland, Coteau des Prairies, and eastern part of the Southern Plateaus physical divisions of Flint (1955) (Sando, 1998). It is in South East (SD09) climate division. The study area was selected based on the availability and quality of historical data to achieve

the research goals, the climate variability concerns, and the development that results with increased runoff causing flooding.

2.2.2. Data acquisition

The monthly summarized historical precipitation data (described as rain and liquid equivalence of snow Fall (melted snowfall) from Sioux Falls Foss Field weather station ID 397667 (Coop) was obtained from the High Plains Regional Climate Center (HPPCC) CLIMOD (CLIMOD, 2020). The monthly precipitation from 1894 to 2019 period of record was used. This station had the longest period of record (127 years) with consistent data with less missing data in eastern South Dakota. HPRCC provides data and the number of days missing. For one day missing data, total monthly value is recorded along with total number of days missing. Where more than 1 day is missing in a month, an M indicating missing is recorded and the missing count is given. The data also had traces labeled as T where precipitation was less than 0.01 (in). The GIS data layers were acquired from Geospatial Data Gateway (USDA, 2020) to create study area maps.

2.2.3. Quality control

The problem with historical data is dealing with gaps in data. To overcome this, quality control is usually performed to assess the quality of data and fill the gaps. In this study, quality control was performed to estimate missing data and traces. There was 0.2 % and 0.02 % of data missing and traces, respectively. Traces are precipitation less than 0.01 (in) that cannot be measured by gauges. The user decides on how to treat traces therefore it is not unreasonable to use 0.01 (in) to fill traces since a trace is a value

greater than zero but less than 0.01 (Yang et al., 1999) therefore, 0.01 (in) was used to fill in traces in this study since it is monthly data which is the summation of daily traces.

To estimate missing data, two approaches were applied. Where 1 to 5 days are missing in a month, the monthly total was used disregarding the missing days, following National Climate Data Center (NCDC, 2021) data guidelines. Where more than 5 days are missing, linear regression approach was used to estimate the missing value. Linear regression approach involves the identification of potential stations with sufficient data length like the station to be estimated, calculation of correlation between stations, ranking of correlations of stations, and then estimating missing months using linear regression of the station with highest correlation and data in the same month (Iqbal et al., 2018; Tardivo & Berti, 2012; Villazón & Willems, 2010). In this study, the stations within 35 miles from the main station with missing data were used, adopting the knowledge that precipitation vary within a shorter distance. Since the study uses the longest records available, only three stations within the distance with similar records were considered in estimating missing data for Sioux Falls Airport station. The station with highest correlation was used which was Canton ID (Coop) 391392. Canton is closer (20 miles) compared to other alternative stations and Canton falls in the same climate division as the main station. The stations information is in Table 2.1.

Table 2.1. Precipitation station's information considered in estimating missing data. Main station and alternative stations that are considered in estimating main station's data.

Stations	Name	ID (Coop)	County	Climate division	Elevation (Feet)	Latitude	Longitude	Available data	Distance from main station
Main	Sioux Falls Foss Field	397667	Minnehaha (FIPS 46099)	South East (SD09)	1428	43.5778	-96.7539	1893-2019	-
Alter. Station	Canton	391392	Lincoln (FIPS 46083)	South East (SD09)	1316	43.3112	-96.5877	1896-2019	20
Alter. Station	Flandreau	392984	Moody (FIPS 46101)	East-Central (SD07)	1567	44.0516	-96.5927	1893-2019	32
Alter. Station	Wentworth	399042	Lake (FIPS 46079)	East Central (SD07)	1722	44.0083	-97.0041	1893-2006	30

2.2.4. Statistical methods

The following statistical procedure was used to analyze precipitation data.

2.2.4.1. Skewness

Skewness is a measure of the degree of asymmetry of a distribution. A normal distribution is symmetric about the mean with a bell-shaped frequency curve (Yamane, 1973). A distribution is skewed if the tail on one side of the distribution is longer than the tail on the other side. If the data is skewed in the direction of higher values, it is positive skewed, if it is skewed in lower values, it has a negative skewness. In a perfect distribution called symmetric, there is no skewness and the skew value will be zero (Freund et al., 1927). If the skewness is less than -1 or greater than 1, the distribution is highly skewed. If skewness is between -1 and -0. 5 or between 0.5 and 1, the distribution is moderately skewed. If skewness is between -0.5 and 0.5, the distribution is approximately symmetrical (GoodData, 2019). The equation for skew function in excel is (Microsoft, 2021):

$$\frac{n}{(n-1)(n-2)}\sum\left(\frac{x_i-\mu}{\sigma}\right)^3 \qquad (1)$$

Where n is number of values, μ is mean, x is observed value.

2.2.4.2. Average (Mean)

Mean is the sum of all observed values divided by number of values (Freund et al., 1927). It is commonly referred to as average. It is defined by:

$$\mu = \frac{1}{\mathrm{n}}\sum_{i=1}^{n} x_i \qquad (2)$$

Where μ is mean, n is number of values, x is observed value.

2.2.4.3. Standard deviation

The standard deviation (σ) of a data set is the positive square root of its variance (Freund et al., 1927; Yamane, 1973). The variance of a data set is the measure of how much values in a dataset differ from their mean. It is the squared difference from the mean. The standard deviation is the calculation of how much a data set deviates from its mean. A low standard deviation indicates values tend to be closer to the mean (expected value) of the data set while high standard deviation indicates values are spread out over a wide range.

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{n}} \tag{3}$$

Where σ is standard deviation, μ is mean, n is number of values, x is observed value.

2.2.4.4. Coefficient of variation

The coefficient of variation (CV) is the ratio of the standard deviation to the mean, expressed in percentage terms. It is a statistical measure of dispersion of data points in a data series around the mean. It is helpful in comparing the degree of variation from one data set to another. It does not reveal much unless it is compared to the mean. For example, CV =10% is a smaller variation than CV = 100 (Freund et al., 1927). The lower the percentage, the less variation. It is defined as

$$CV = \frac{\sigma}{\mu} . 100 \tag{4}$$

Where σ is standard deviation, μ is mean.

CV is used frequently in hydrology to provide an indication of interannual and seasonal variability of hydroclimatic conditions of region.

2.2.4.5. Percent Difference

Percent difference (% diff) is the change over time and measures how much something has changed. It is used to calculate the amount of change compared to initial value.

$$\%Diff = \left(\frac{(New\ value - Old\ value)}{Old\ Value}\right) * 100 \qquad (5)$$

Where percent difference could not be calculated due to division by zeros, the difference or deviation from the average in inches was used.

Percent difference was used to quantify the increase or decrease from the average climate. Skewness was used to check for distribution of data. Mean and standard deviations were used to understand the data and its distribution and variability to create climate classifications of data. The coefficient of variation was used to determine which year, season and month was the most variable from the mean. The standard deviation and mean together provide a good amount of information about the distribution of data even though they are only two descriptive measures (Freund et al., 1927). These statistics are appropriate as the measure of dispersion of precipitation and distribution of the dataset.

2.2.5. Data analysis

After quality control and gap filling were performed, data analysis was performed following the flowchart in Figures 2.3 which summarizes the steps followed in analyzing data.

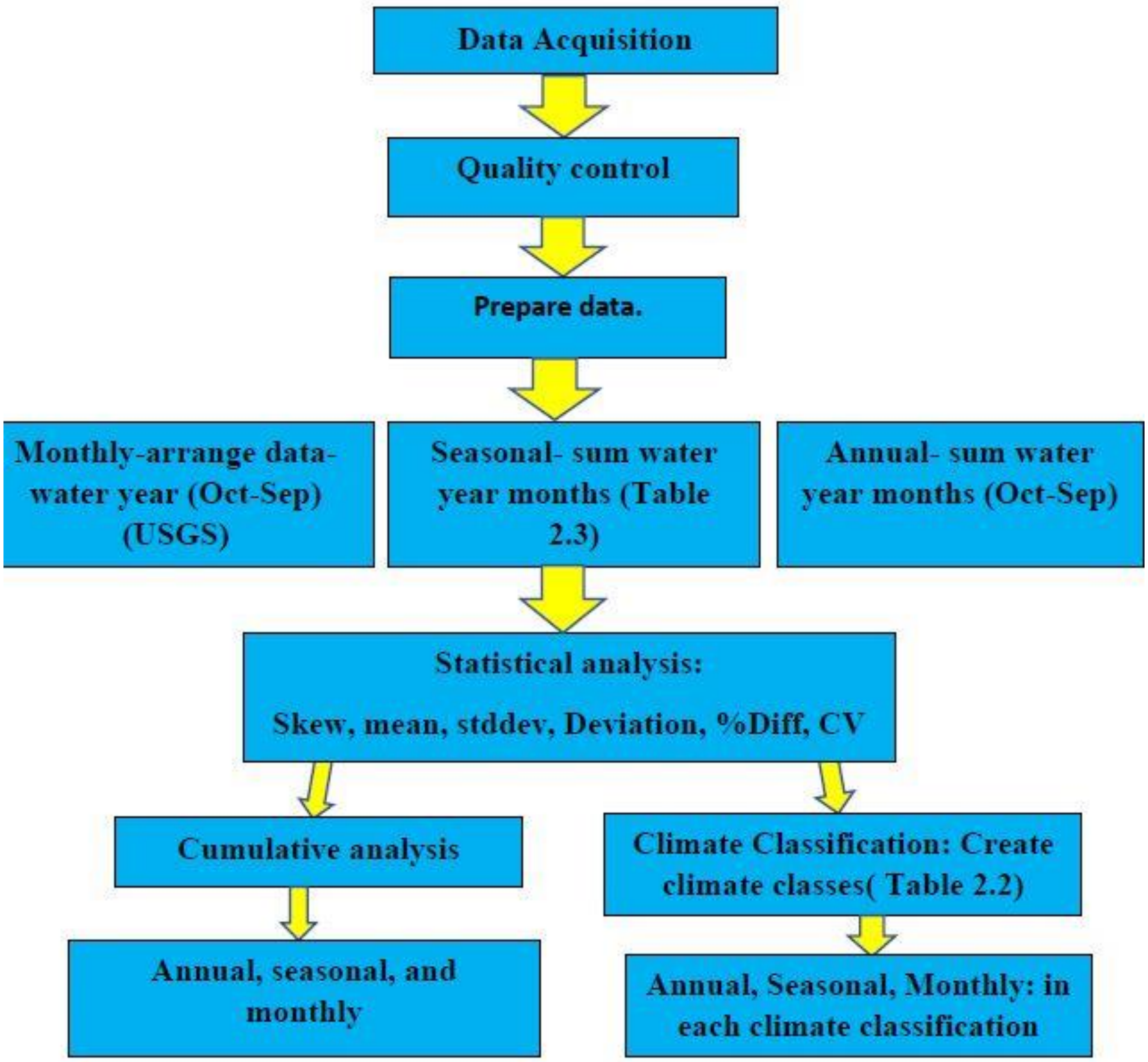


Figure 2.3. The flowchart showing steps in data analysis.

2.2.5.1: Annual analysis

Monthly data that was originally downloaded in regular year format (January to December), was aggregated into a water year. According to United State Geological Survey (USGS), water year starts from October 1st to September 30th of the following year. The year that has 9 months out of 12 is the water year. That is, 2019 water year is from October 1st, 2018 to September 30th, 2019 (USGS, 2019). Therefore, the word year in this study will mean water year. The sum of all the months in the water year was calculated to obtain annual precipitation of that year. Then data was checked for normal distribution by computing its skew. Since skew was 0.34, which is between -0.5 and 0.5, for this study, data considered was normally distributed and ready for further analysis. Then data was used to perform further statistical analysis. First, the average (mean) was calculated. then, the standard deviation and the minimum and maximum values were also calculated. Then the average and standard deviation were used to create climate classifications.

2.2.5.2. Climate Classifications

The average and standard deviation of annual accumulated precipitation were used to classify precipitation into climate categories. Years were classified as Very Wet ,Wet, Average, Dry, and Very Dry years, using the criteria in Table 2.2.

Table 2.2. Description of criteria used in classifying climate.

	Parameter	Classification
Above	Average + 1.5*Standard Deviation	Very Wet
Between	Average + 1.5*Standard Deviation & Average + 0.5*Standard Deviation	Wet
Between	Average + 0.5*Standard Deviation & Average - 0.5*Standard Deviation	Average
Between	Average - 0.5*Standard Deviation & Average - 1.5*Standard Deviation	Dry
Below	Average - 1.5*Standard Deviation	Very Dry

*indicates multiply, + indicates addition, and -indicates minus

2.2.5.3 Seasonal analysis

Monthly data for each water year was converted to seasons by summing up the months to construct seasons, according to Table 2.3. After seasons were created, the data was checked for normality by computing skew for each season and the skewed data was transformed using log to make it normally distributed. The mean, maximum, minimum and CV were calculated for all seasons for all the years. Then data was analyzed for each climate classification created above (Very Wet, Wet, Average, Dry, and Very Dry), following the same statistical procedure. Seasonal precipitation variability was analyzed and compared against each season and within their respective climate classes.

Table 2.3. Months in each season according to water year (USGS, 2019).

Seasons	Months
Fall	October-November-December
Winter	January-February-March
Spring	April-May-June
Summer	July-August-September

2.2.5.4: Monthly analysis

First monthly data for each year was arranged according to water year, that is from October 1st to September 30th. Cumulative monthly data for all the years was analyzed for monthly precipitation variability. The data was analyzed following similar statistical procedure described above. For all the years, monthly data was analyzed for precipitation variability and to compare the months. Then monthly data was analyzed for each climate classification following the same statistical procedure.

2.3. Results and Discussion

The results demonstrate the methodology for quantifying climate variability using 125 years of precipitation data from Sioux Falls Foss Field weather station. The results present annual, seasonal, and monthly precipitation variability analyzed as cumulative precipitation variability and climate classifications variability.

2.3.1. Annual analysis

2.3.1.1. Annual Cumulative analysis

The results show that annual precipitation from 1895-2019 water years ranged from 13.2 in in 1976 to 43.1 in in 2010 (Figure 2.4). The average precipitation for all 125 years is 26 (in) and the standard deviation is 5.4 (in). Even though precipitation is fluctuating, Figure 2.4 shows that precipitation shows a slight linear increase over time indicating general increase over time with a slope of 0.0092. The annual precipitation CV was 21 % indicating smaller interannual variability meaning year to year precipitation slightly vary from the mean.

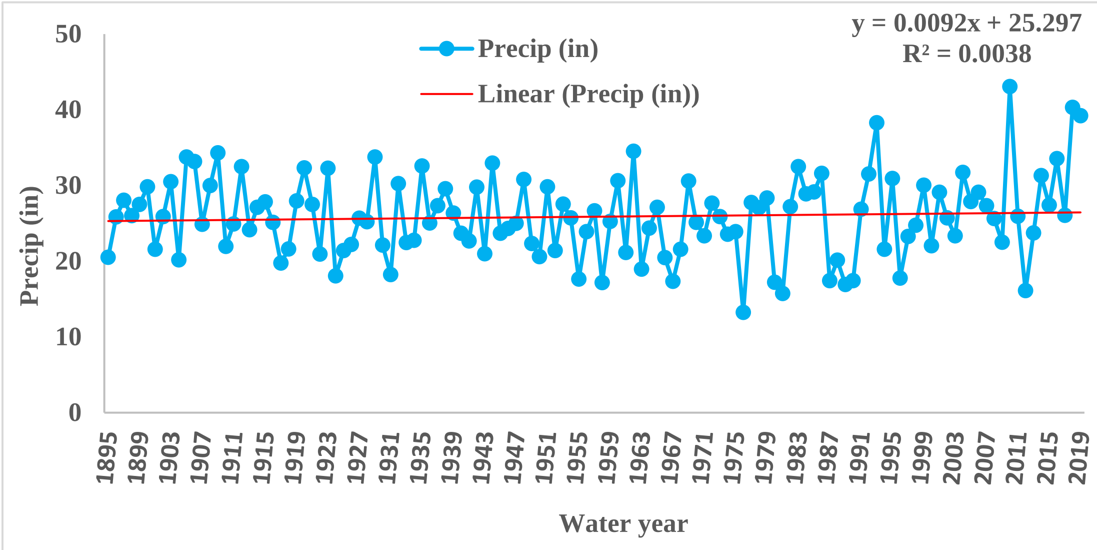


Figure 2.4. Annual precipitation from 1895-2019 (125 years) and linear trend line (red color).

The deviation from the mean precipitation is highest in 2010 with 17.2 inches, 66 % increase and the lowest is in 1976 with -12.7 inches, a 49 % decrease meaning higher increase than decrease from the mean (Figure 2.5).

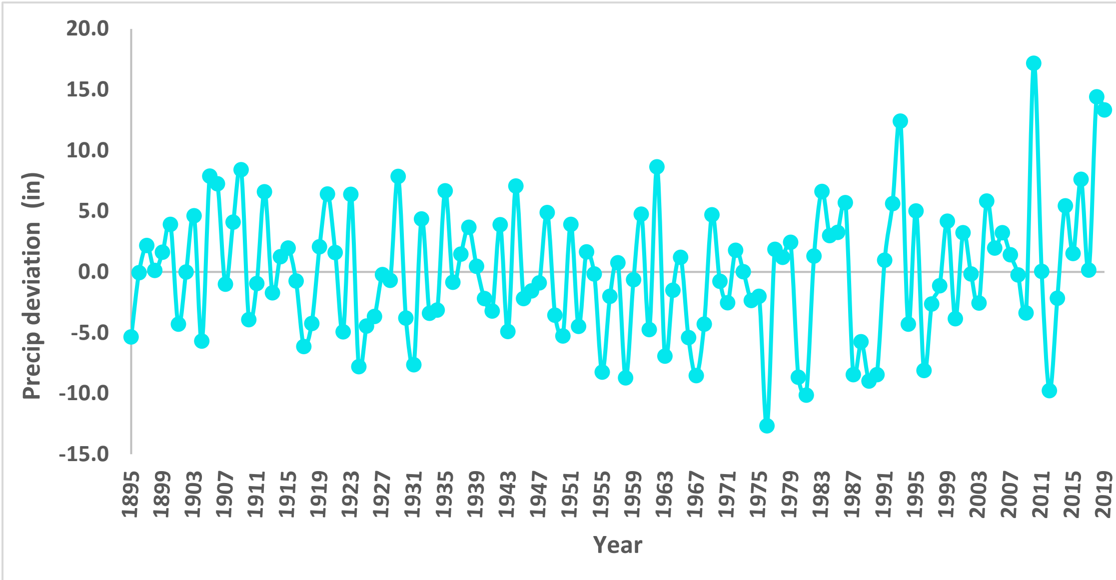


Figure 2.5. The deviation from the mean precipitation for 1895-2019.

2.3.1.2: Annual analysis for Climate classes

Table 2.4. shows the parameters used to classify climate, where precipitation above 33.9 in was Very Wet, between 33.9-28.6 in Wet in, between 28.6-23.2 in average, between 23.2-17.8 Dry, and below 17.8 in Very Dry. Figure 2.6 shows the dividing lines for classified climate.

Table 2.4. Precipitation limit parameters used as cutoff limits to classify climate into Very Wet, Wet, average, Dry, and Very Dry.

	Parameter (in)	**Classification**
Above	33.9	Very Wet
Between	33.9-28.6	Wet
Between	28.6-23.2	Average
Between	23.2-17.8	Dry
Below	17.8	Very Dry

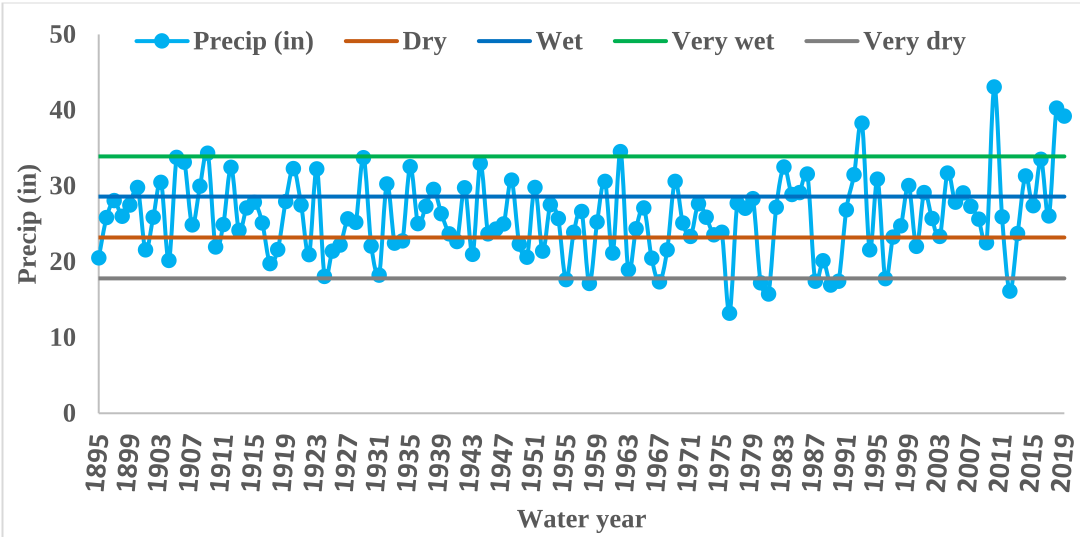


Figure 2.6. The annual precipitation and cutoff lines for the climate classes Very Wet (light green), Wet (blue), Dry (brown), and Very Dry (grey).

The number of average precipitation years are highest, followed by Wet, Dry, Very Dry, and Very Wet (Table 2.5). Even though the number of Very Wet, Wet, Dry, and Very Dry years is lower than the average years, they have the highest impact on society by leading to floods and drought. The recent years (2000s) mostly Fall in Very Wet, Wet, and average climate and the last 2 years are in Very Wet climate (2018 and 2019). Less 2000s years in Dry and Very Dry climates and the 1800s are more in average years. Precipitation in climate classes ranged from 34.3 in. in 1909 to 43 in. in 2010, 28.9 in. in 1984 to 33.8 in. in 1905, 23.2 in. in 1997 to 28.3 in. in 1979, 17.8 in. in 1996 to 22.7 in. in 1934, 13.2 in. in 1976 to 17.6 in. in 1955 for Very Wet, Wet, average, Dry, and Very Dry, respectively. The Wettest year in the Very Wet climate is 2010 and the least is 1909, The driest year in the Very Dry climate is 1976 and the least Very Dry is 1955.

Table 2.5. Years in each climate classification and their totals in brackets.

Very Wet (6)	**Wet (30)**		**Average (51)**		**Dry (28)**		**Very Dry (10)**
2010	2016	1908	2017	1956	2009	1904	2012
2018	2014	1906	2015	1954	2000	1901	1990
2019	2006	1905	2013	1953	1996	1895	1989
1993	2004	1903	2011	1947	1994		1987
1962	2001	1900	2008	1946	1988		1981
1909	1999		2007	1945	1968		1980
	1995		2005	1940	1966		1976
	1992		2003	1939	1963		1967
	1986		2002	1937	1961		1958
	1985		1998	1936	1952		1955
	1984		1997	1928	1950		
	1983		1991	1927	1949		
	1969		1982	1921	1943		
	1960		1979	1919	1941		
	1951		1978	1916	1934		
	1948		1977	1915	1933		
	1944		1975	1914	1931		
	1942		1974	1913	1930		
	1938		1973	1911	1926		
	1935		1972	1907	1925		
	1932		1971	1902	1924		
	1929		1970	1899	1922		
	1923		1965	1898	1918		
	1920		1964	1897	1917		
	1912		1959	1896	1910		
			1957				

On average, the precipitation deviation of climate classes from the average climate in Figure 2.7 shows that Very Wet climate varies the most from the average climate followed by Very Dry, Wet, and Dry climate. The Very Wet climate and Wet climate are higher than average climate by 48% (12.5 in) and 21% (5.3 in) respectively while Very Dry and Dry climates are lower than average climate by 36 % (9.2 in) and 19% (4.8 in) respectively. The averages and CVs for climate classes (Figure 2.8) were 38 ,31, 26, 21, and 17 in and 9, 5, 6, 7, and 8 (%) for Very Wet, Wet, average, Dry and Very Dry respectively, and CVs are very low, indicating lower degree of variation from their mean in each climate class (Figure 2.8). However, in comparison, Very Wet and Very Dry climates have higher CVs indicating higher variation from their mean.

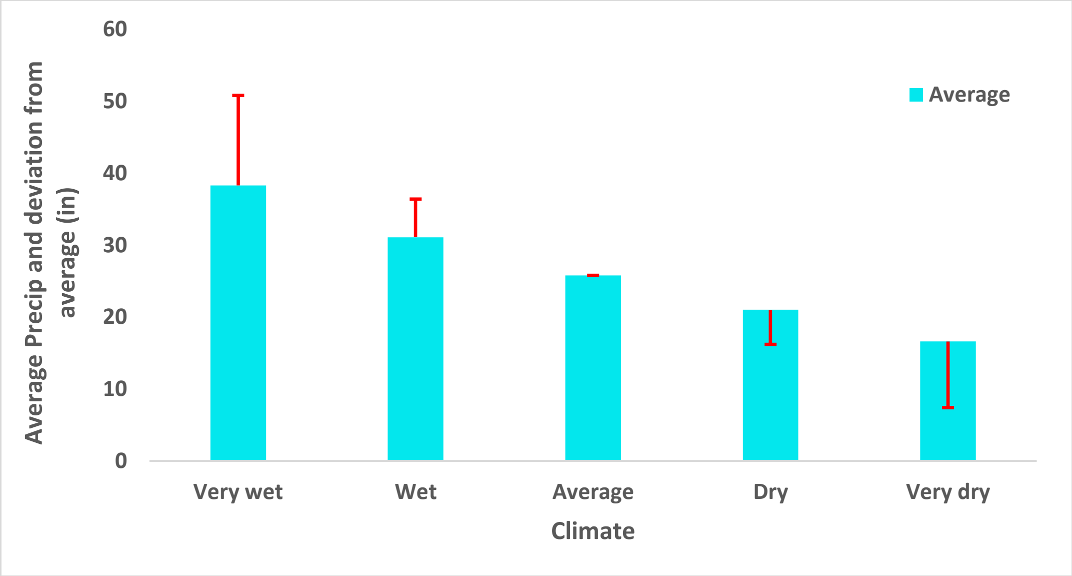


Figure 2.7. Average climate precipitation and their difference from the average climate (red bars).

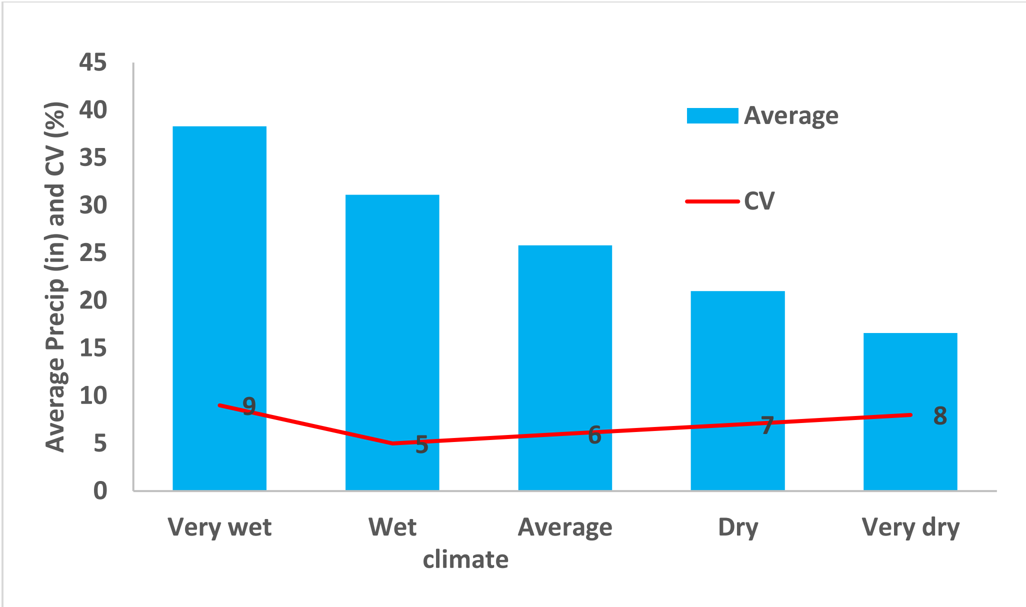


Figure 2.8. Average precipitation and CVs for climate classes.

2.3.2. Seasonal results

Results for seasons ; Fall, Winter, Spring, and Summer according to water year.

2.3.2.1: Cumulative analysis

Seasonal results shown in Figure 2.9 show that seasonal precipitation varies with years, but it is linearly increasing in Fall, and Winter and decreasing Spring and Summer. Generally, for all the water years, Spring had the highest precipitation followed by Summer, Fall, and then Winter with the lowest precipitation. The seasonal precipitation ranged from 0.4in. in Winter and 19.3 in. in the Summer. Spring and Summer differ with years, some years have highest precipitation in the Spring, and some have highest in the Summer. Spring ranged from 4.2 to 17.3 in, and Summer from 3.1 to 19.3 in with the totals of 1293 in and 1135 in respectively, while Fall ranged from 0.5 to 10.1 in and

Winter from 0.4 to 6.7 in with totals of 452 and 354 in respectively for all 125 years. The average precipitation for Spring, Summer, Fall, and Winter are 10, 9, 4, and 3 (in) respectively with standard deviations of 3, 3, 2 and 1 (in), respectively (Figure 2.10)

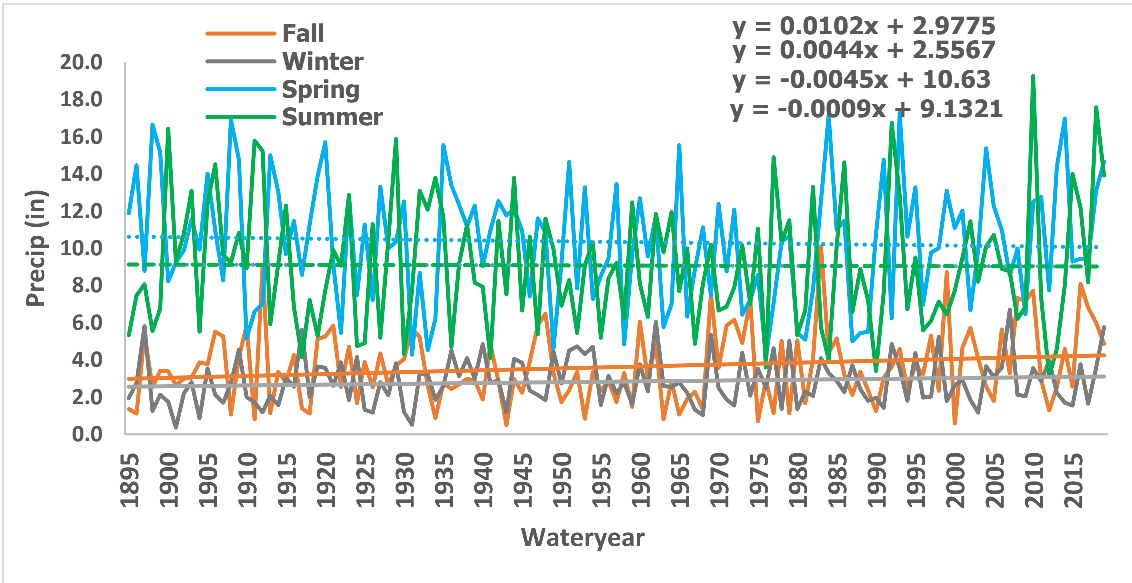


Figure 2.9. Seasonal precipitation for 1895-2019 and trendlines and their equations for each season.

For all the years, the CV for Fall, Winter, Spring, and Summer were 55, 45, 31, and 37 (%) respectively, showing Fall to be the most variable season followed by Winter, Summer, and Spring which is the least variable (Figure 2.10) meaning precipitation varies more in the Fall due scare precipitation and a lot of zero precipitation while Spring precipitation does not vary much from the mean due to higher frequency of precipitation.

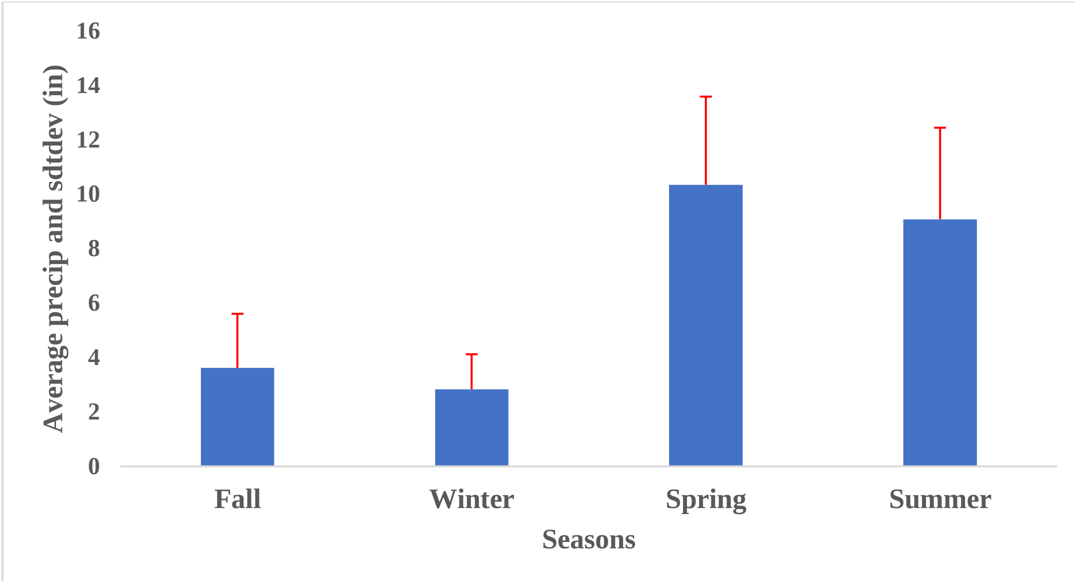


Figure 2.10. Average seasonal precipitation and their standard deviation (red bars).

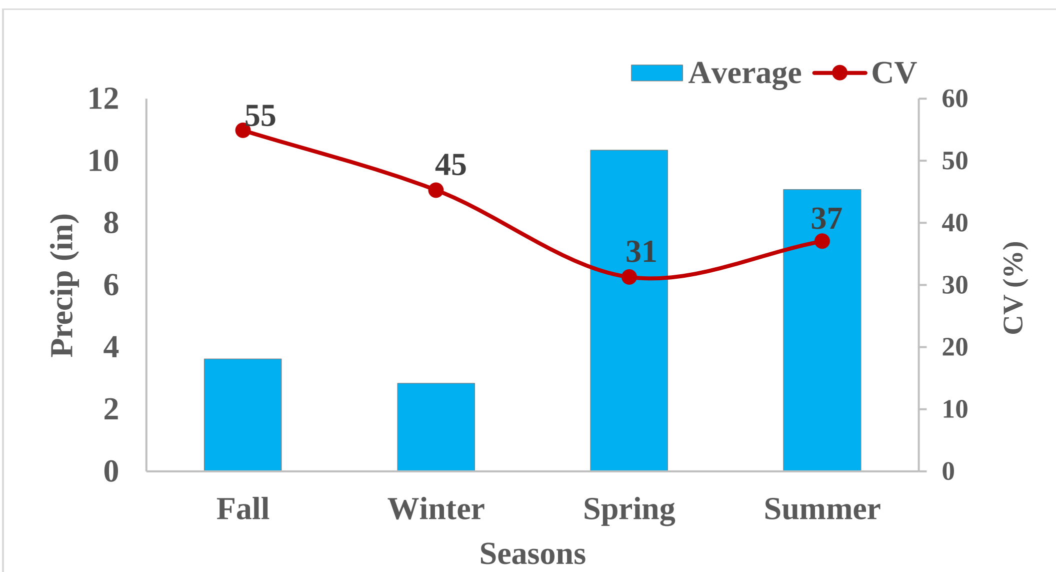


Figure 2.11. Average seasonal precipitation and their CVs for all the years (1895-2019).

2.3.2.2: Seasonal precipitation in climate Classes

The same seasonal pattern is also observed for seasonal variability in each climate classes; Very Wet, Wet, average, Dry, and Very Dry years. Precipitation varies by years in each climate but generally, Spring has the highest precipitation, followed by Summer, Fall, and Winter, except Very Wet climate has highest precipitation in the Summer (Figure 2.12). The results also show that seasonal precipitation is highest in Very Wet climate and lowest in Very Dry climate.

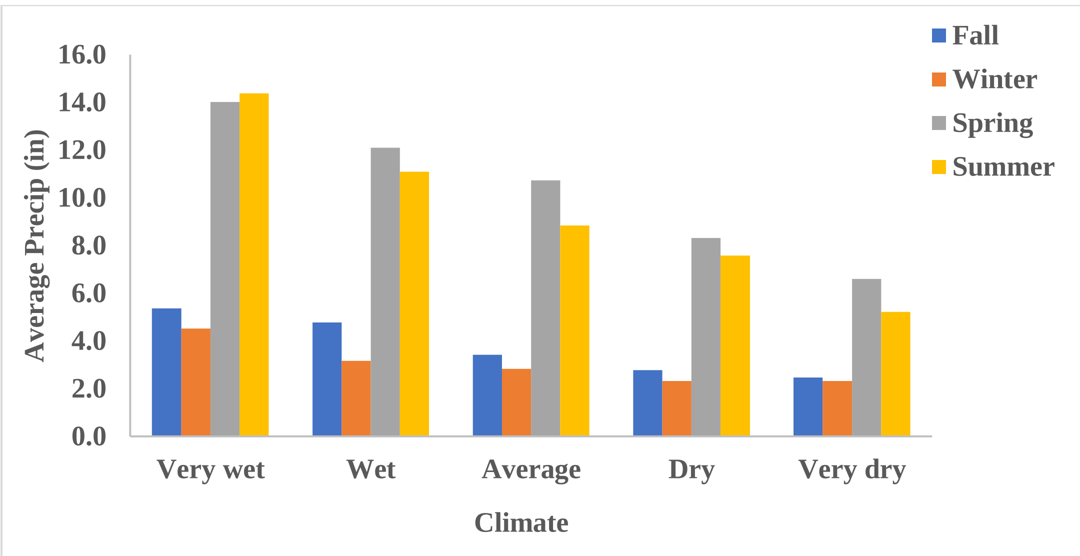


Figure 2.12. Average seasonal precipitation for climate classifications.

For Very Wet climate, Fall, Winter, Spring, and Summer precipitation ranged from 4.1 to 7.7 in, 3.6 to 6.1 in, 11.8 to 17.3 in, and 10.8 to 19.3 in, respectively. For Wet climate, Fall, Winter, Spring, and Summer precipitation ranged from 1.1 to 10.1 in, 1.2 to 5.4 in, 6.3 to 17.2 in, and 4 to 16.8 in respectively. For average climate, Fall, Winter, Spring, and Summer precipitation ranged from 0.7 to 7.3 in, 1.2 to 6.7 in, 6.4 to 16.7 in,

and 4.6 to 15.8 in respectively. For Dry climate, Fall, Winter, Spring, and Summer precipitation ranged from 0.5 to 7.2 in, 0.4 to 5.6 in, 4.3 to 12.5 in, and 4.1 to 13.8 in respectively. For Very Dry climate, Fall, Winter, Spring, and Summer precipitation ranged from 1.3 to 5.1 in, 1.3 to 4.0 in, 4.2 to 10.8 in, and 3.1 to 7.2 in, respectively.

The average seasonal precipitation for Very Wet, Wet, Average, Dry, and Very Dry climate ranged from 4.5 in. in Winter to 14.4 in. in Summer, 3.2 in. in Winter to 12.1 in. in the Spring, 2.8 in. in Winter to 10.7 in in the Spring, 2.3 in. in the Winter to 8.3 in. in the Spring, and 2.3 in. in the Winter to 6.6 in. in the Spring, respectively (Figure 2.12). The seasonal deviation of Very Wet, Wet, Dry, and Very Dry climates from the average climate shown in Figure 2.13 shows high increase in the Summer for Very Wet (5.5 in) and Wet (2.3 in), followed by Spring, Fall, and Winter while there is highest decrease in the Spring for Very Dry (4.1 in) and Dry climates followed by Summer, Fall, and Winter.

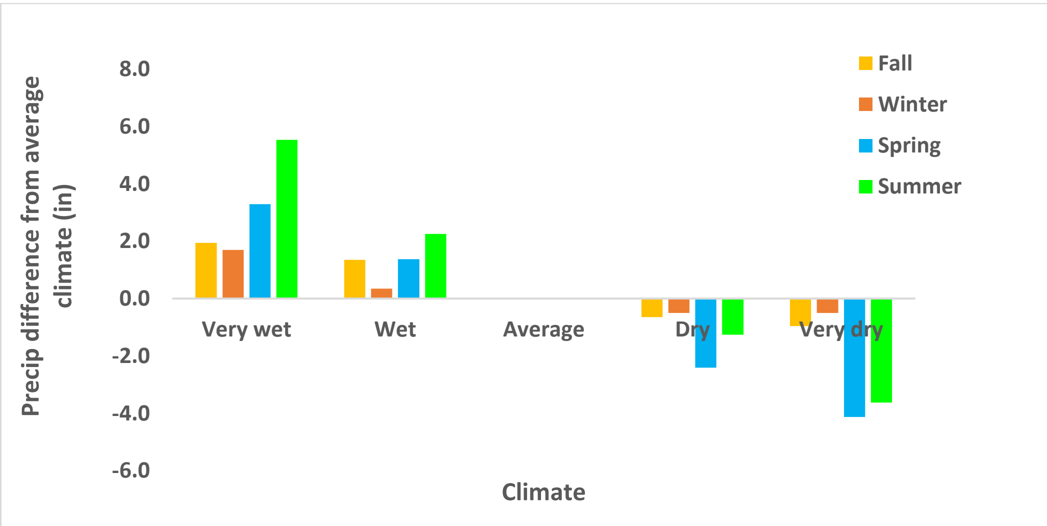


Figure 2.13. Seasonal precipitation difference of climate classes from the average climate.

The CVs in Figure 2.14 show that in all climate classes, Fall has highest CV followed by Winter, Summer, and Spring with the lowest, except in Very Dry climate,

Spring has high CV than Summer. This means Fall is the most variable season and Spring is the least variable. Generally, Dry climate shows high seasonal variability ranging from 61% in Fall to 33% in the Spring while Very Wet climate shows the least variability ranging from 24% in the Fall to 14% in the Spring. Dry climate has highest seasonal variability followed by average, Wet, Very Dry, and Very Wet.

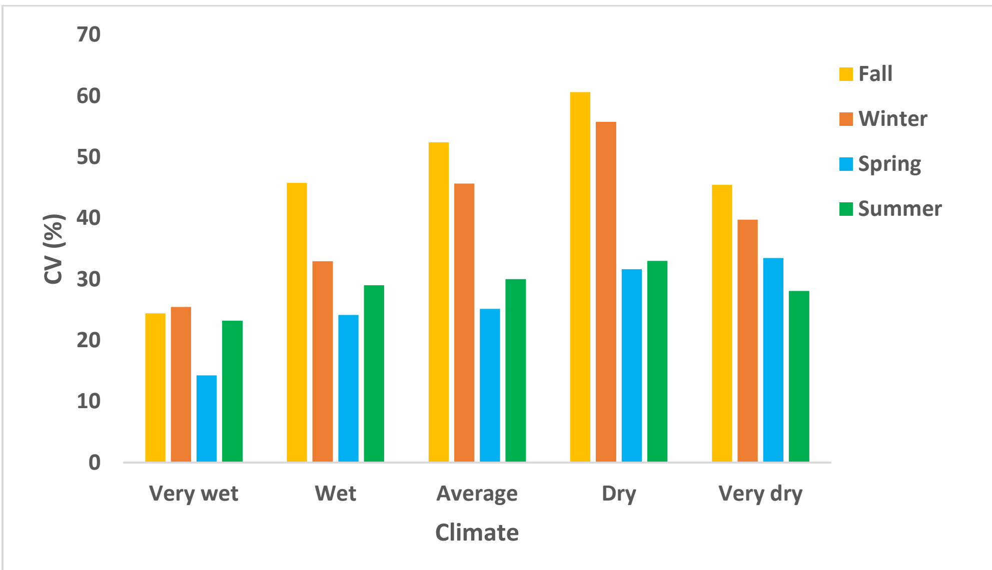


Figure 2.14. Seasonal CV (%) showing seasonal variability in each climate class.

2.3.3. Monthly analysis

2.3.3.1: Cumulative analysis

The precipitation shows similar monthly patterns for all the years as expected based on the climate region (Figure 2.15). Generally, for all the years, precipitation showed to be lowest in January and gradually increase with each month until June which is the peak and gradually decrease again until January which is the lowest. Monthly

precipitation from 1895-2019 varied from 0.0 in to 13.7 in. in 2014 (Figure 2.15), averages ranged from 0.6 in in January to 4.2 in. in June. May, June, July, August, and September have high precipitation even though each year is different. June shows to have the extreme in 2014 with 13.7 in which is 9.5 in higher from average precipitation.

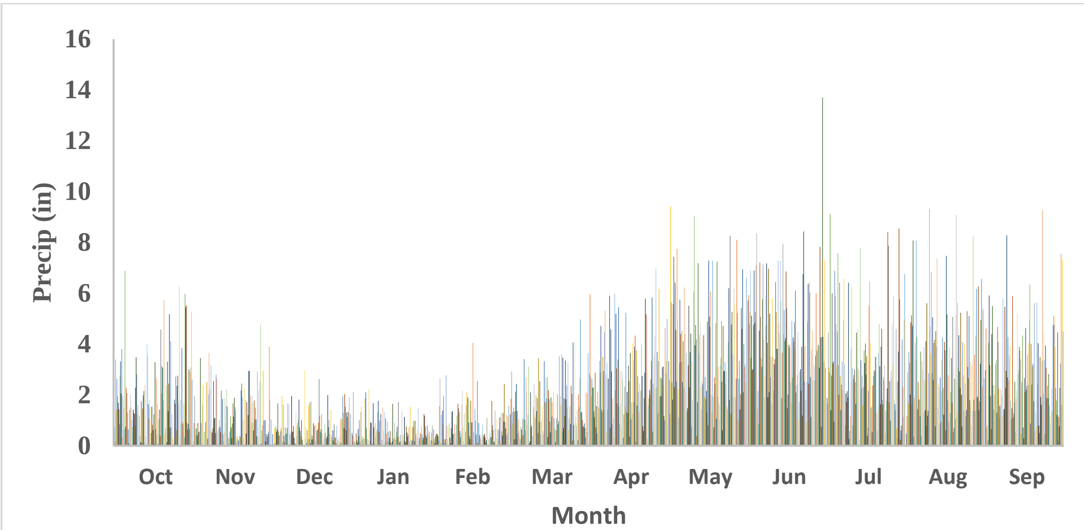


Figure 2.15. Monthly precipitation from October to September for a period of 1895-2019.

The CV for all the months in Table 2.6 ranged from 48% in June to 89.9% in November, indicating June to be the least variable and November the most variable month. Generally, the higher the precipitation, the lower the CV and vice versa.

Table 2.6. Monthly CV, and average precipitation for the period of 1895-2019. Highlighted in green are minimums and highlighted in blue are maximums.

Month	CV (%)	Average (in)
Oct	83.0	1.8
Nov	89.9	1.1
Dec	83.2	0.7
Jan	86.7	0.6
Feb	89.4	0.8
Mar	69.1	1.5
Apr	59.0	2.6
May	56.9	3.6
Jun	48.1	4.2
Jul	63.8	3.1
Aug	62.7	3.2
Sep	63.4	2.8

2.3.3.2: Climate classes

The same precipitation pattern is observed for climate classes; Very Wet, Wet, average, Dry, and Very Dry (Figure 2.16). Precipitation is lowest in January and gradually increase with each month until June which is the peak and gradually decrease again until January which is the lowest except Very Wet climate has a peak in July. Average precipitation for Very Wet, Wet, average, Dry, and Very Dry ranged from 0.8 in in January to 6.4 in in July, 0.6 in in January to 4.6 in in June, 0.5 in in January to 4.2 in in June, 0.5 in in February to 3.9 in in June, and 0.3 in in December and January to 2.7 in

in June, respectively (Figure 2.16). CV ranged from 25 % in July to 73 % in November and 56% in June to 92% in February for Very Wet and Very Dry years, respectively.

The precipitation deviation from the mean is an increase of 48% in Very Wet and 21% in Wet and decrease of 36% in Very Dry and 19% in Dry climate (Figure 2.17). This shows that the increase is higher than decrease and Very Wet and Very Dry have highest deviations.

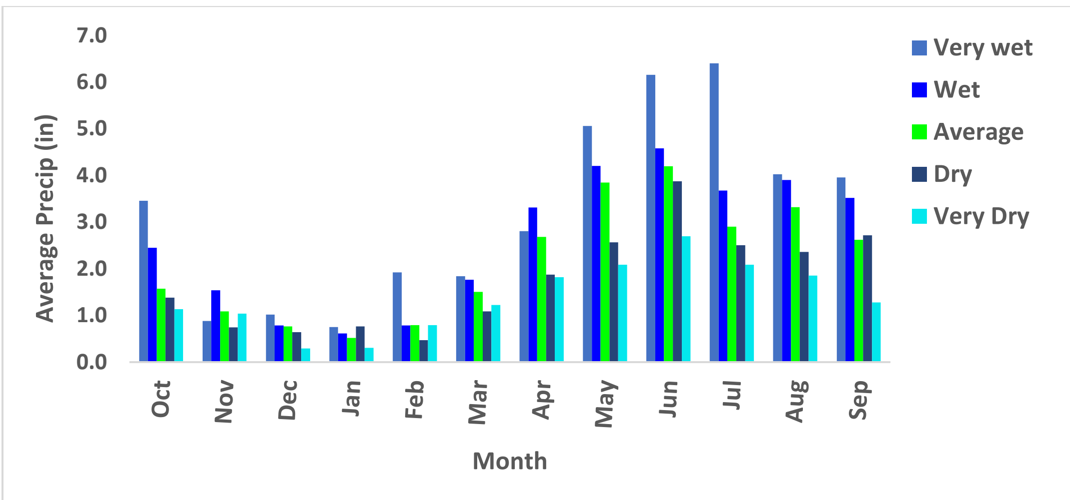


Figure 2.16. Average monthly precipitation for climate classes: Very Wet, Wet, average, Dry, and Very Dry climate-1895-2019.

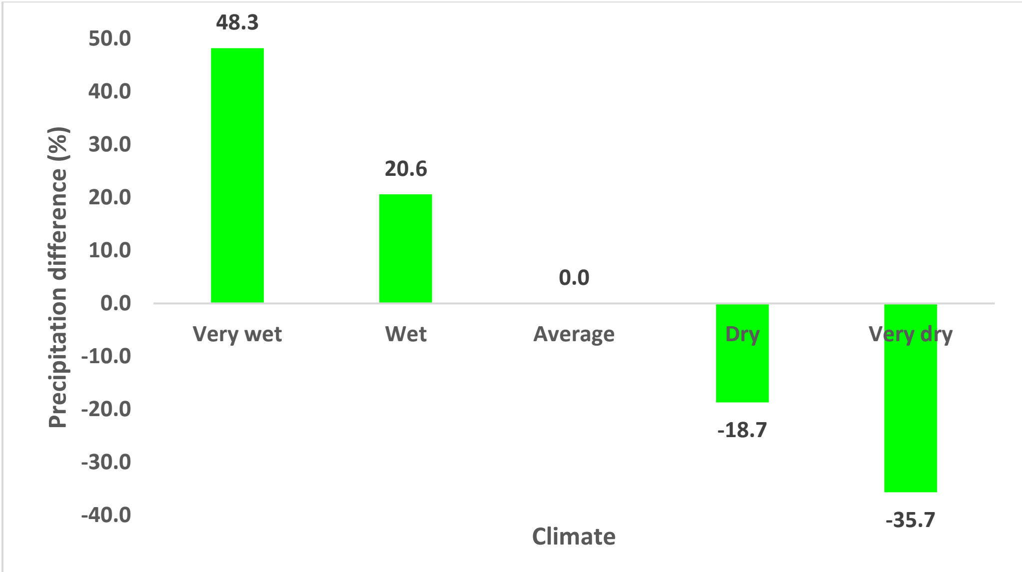


Figure 2.17. Monthly precipitation differences of climate classes from the average climate. Positive values mean increase and negative means decrease.

Figure 2.18 shows that generally, the CV is higher from October to March (Fall and Winter months) indicating high precipitation variability, and lower from April to September (Spring, and Summer months) indicating lower variability in precipitation around the mean. The CV ranged from 25% in July to 73% in November for Very Wet, 46% in May to 83% in January and February for Wet, 40% in June to 97%in January for average, 45% in June to 101% in November for Dry, and 48% in August to 92% in February for Very Dry. Very Wet climate has lower CV meaning less variation from the mean and Dry years have high CV meaning monthly precipitation is more variable from the mean. This indicate that November and January are highly variable months and June, and July are less variable.

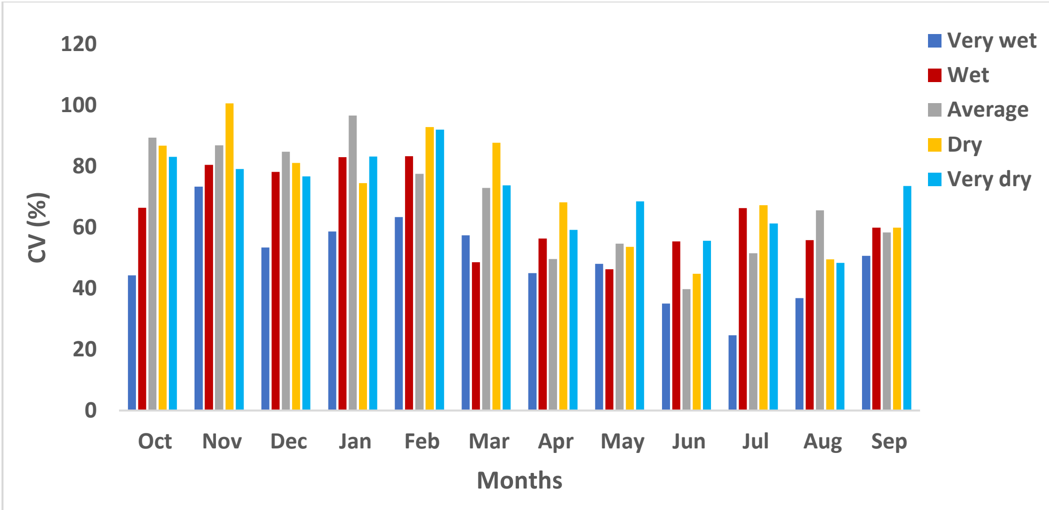


Figure 2.18. CV in percentage for monthly precipitation for Very Wet, Wet, average, Dry, and Very Dry climates.

2.4. Discussion Summary

Precipitation data from 1895 to 2019 was analyzed using the statistical methods described above. Precipitation varies yearly, seasonally, and monthly, but overall, it is linearly increasing over time. The linear increase agrees with precipitation trends showing precipitation increase over time in the U.S (National Climate Assessment, 2021). For 125 years, 2010 was Wettest (43.1 in) while 1976 was driest (13.2 in),

This agrees with (Amatya 2011; Basnet 2011; Kshatriya 2018) who found 1976 as the dries year while they found the wettest year as 1999 in Aberdeen. This indicates 1976 as the driest year for the period of record. The differences in the results may be due to the different range of data used as this study used longest record 1895-2019 while others used shorter periods of record (1949- 2009 for Amatya, 1928-2008 for Basnet, and 1955 to 2017 for Kshatriya). These studies analyzed results as an 8-year cycle not annual while this study performed annual analysis. Also, the climate division is different as some

studies are done in northern South Dakota and some even though in eastern South Dakota in different climate division from this study. In comparison to the notion that climate in this state (SD) is an 8-year cycle, Basnet (2011) used 1928- 2008 data and found 1969-1976 to be driest period and they found 1993-2000 as Wettest 8-year period, while this study found some years during this period as either Very Wet, (1993) Wet, Average, and Dry (1994 and 2000).

Precipitation is highly variable in the study area, indicating a less predictable climate and a challenge for reliable water resources and a challenge for rainfed agriculture which is a common practice in the study area. This makes early preparation for extremes such as floods and drought a challenge as forecasting needs to be done early before extremes occur.

The highest seasonal precipitation is in the Summer (19.3 in) in 2010 and lowest was in the Winter (0.4 in) in 1901. However, on average, precipitation is highest in the Spring. Generally, there is more precipitation in the Spring and Summer months; May June, July, August, and September and less in the Winter and Fall months. Each year varies, and this creates less certainty in which month has highest precipitation as some years gets highest precipitation in May and some up to September, hence a challenge in managing and planning for floods and droughts that need early forecast. Less precipitation in the Winter due to the cold weather and precipitation fall as snowfall, with January having the lowest precipitation.

The highest monthly precipitation is in June with 13.7 in in 2014, a 9.5 in increase from average. Generally, January has lowest precipitation and June the highest. The CVs show that June is less variable, and November is highly variable month. This could be

due to the scarce precipitation in November. Generally, months, seasons and years with high precipitation have less variable precipitation and the ones with less precipitation have highly variable precipitation from the mean. Very Wet climate has highest precipitation in July while Wet, Average, Dry, and Very Dry have highest in June.

Generally, years vary, some years are Very Wet in the Spring some in the Summer due to the timing and the intensity of precipitation rather than frequency, which agrees with (Bishop et al., 2019; Powell & Keim, 2015). In comparison with other studies, this study found Spring to have highest precipitation except for Very Wet climate which had highest in Summer. This agrees with thesis work done in the northeastern South Dakota region (Basnet 2011; Kshatriya 2018) that the precipitation records in the Spring and Summer lead to a Wet or Dry period, however, precipitation from Fall could lead to a Wet or Dry year. Basnet (2011) found Summer to have highest precipitation, while this study found on average Very Wet climate has high average precipitation in the Summer.

This shows that precipitation is variable, and it could make predictions and early preparations of droughts or floods hard and the timing and availability of water resources less predictable.

2.5. Conclusions

The goal of this study was to quantify Sioux Falls Foss Field station historical precipitation from 1895-2019, 125 years. The results show that:

- 2010 has highest precipitation (43.1 in) and 1976 has lowest precipitation (13.1 in), meaning more increase in precipitation than decrease from long-term average.

The precipitation shows slight linear increase over time however it varies with each year.

- The Very Wet climate and Wet climates are higher than average climate by 48% (12.5 in) and 21% (5.3 in) respectively while Very Dry and Dry climates are lower than average climate by 36 % (9.2 in) and 19% (4.8 in) respectively.
- Spring gets the highest, except in Very Wet climate and less variable precipitation and Winter gets the lowest and highly variable precipitation.
- January has the lowest and highly variable precipitation and June has the highest and less variable precipitation. However, November is the most variable month. The CV is higher from October to March (Fall and Winter months) indicating high precipitation variability, and lower from April to September (Spring, and Summer months) indicating lower variability in precipitation around the mean.
- Year, season, and month with highest precipitation has less variable precipitation (2010, Spring, June) while those with lowest precipitation have highly variable precipitation (1976, Winter and January).

The results show long-term annual, seasonal, and monthly precipitation variability and overall increase over time with more wet extremes in recent years, proving non-stationary precipitation and the need to reevaluate stationarity concept and quantify climate variability at local scale. The methods developed here can generally be applied in any location and for other climate parameters such as temperature, streamflow, and others.

Chapter 3: Quantifying Inter and Intra Annual, Seasonal, and Monthly Precipitation Variability for Extreme Climate (Very Wet and Very Dry Climate Classifications).

Abstract

Worldwide, climate extremes continue to result in severe social and economic impacts. Extreme precipitation cause floods and droughts that severely impact the public. Whether natural or human induced, climate variability creates a less predictable climate and a challenge in floods and drought forecasting and preparation. The need to quantify extreme climate is inevitable to understand their severity and protect the public. This study used statistical tools to quantify extreme climate using data from a Sioux Falls, SD weather station. The Very Wet and Very Dry climate classifications were identified from 1894 to 2019, 125 years of precipitation data and were analyzed and quantified. The results show inter and intra annual, seasonal, and monthly precipitation and snowfall variability. Very Wet shows an increase of up to 70% (2010) in annual precipitation from long-term average and snowfall increase of up to 116% (1962). Very Dry climate shows an annual precipitation decrease of up to 49% (1976) and snowfall decrease of up to 73% (1987). Very Wet has highest precipitation in Summer and Very Dry has highest precipitation in Spring and both have lowest in Winter. Winter has highest snowfall and Spring has lowest for both. Very Wet has highest precipitation in July and Very Dry has highest precipitation in June and both have lowest in January. Snowfall amounts do not correspond with precipitation amounts: some years have high precipitation and low snowfall and vice versa. Both Very Wet and Very Dry have similar number of days and the number of days with precipitation and snowfall do not correspond with the precipitation and snowfall amounts, the magnitude influences the totals.

3.1. Introduction

Climate extremes whether due to natural climate variability or anthropogenic climate change, have become more frequent and intense. Extreme climate and weather events such as storms, floods, drought, heat waves, and others results in loss of lives, damage of property, infrastructure, crops, environment, and economic loss (Heim, 2015; NOAA, 2020; UN, 2002). From 1998 to 2017, losses due to extreme weather events increased 151 percent compared to 20 previous years (UN, 2002). The U.S. had 273 weather and climate disaster events since 1980, with damage or cost of over $1.790 trillion and 14,223 deaths (NOAA, 2020). According to NOAA (2020), 2015-2020 are consecutive years with 10 or more billion-dollar weather and climate disaster events that impacted united states. In addition to major damages, climate extremes affect water availability needed for domestic, industrial, agricultural, and recreation uses.

The climate extremes are thought to be exacerbated by anthropogenic global warming which cause intense and altered precipitation (Bates et al., 2008; C2ES, 2020; Cheng & AghaKouchak, 2014; IPCC, 2007, 2014; Karl et al., 2009) that result in floods and droughts leading to water quality issues, loss of lives, destruction of properties, infrastructure, and economy. The change in climate affects the water cycle by increasing precipitation and runoff, floods and droughts, water quality issues, shifting the timing of runoff in snowpack dominant areas, and affecting timing, location and availability of water (Bates et al., 2008; Karl et al., 2009). Projections and historical records show that frequent and severe extreme climate events are expected to worsen over most areas (Bates et al., 2008; EPA, 2016; IPCC, 2014). Figure 3.1 shows the trend in heavy precipitation and the recent decades (1950s-2000s) show a continuous increase in trend.

In addition to climate, changes in land use due to agriculture, urbanization, industrialization, and population growth exaggerate the effects of extremes by changing the hydrologic response. Increased imperviousness due to development, intensify runoff, water pollution, peak flows, and shorten time to peak, during storm events. (Cristiano et al., 2017). The capacity of drainage systems designed to drain runoff can be exceeded during extreme storm events and this can cause flooding (Qin et al., 2013).

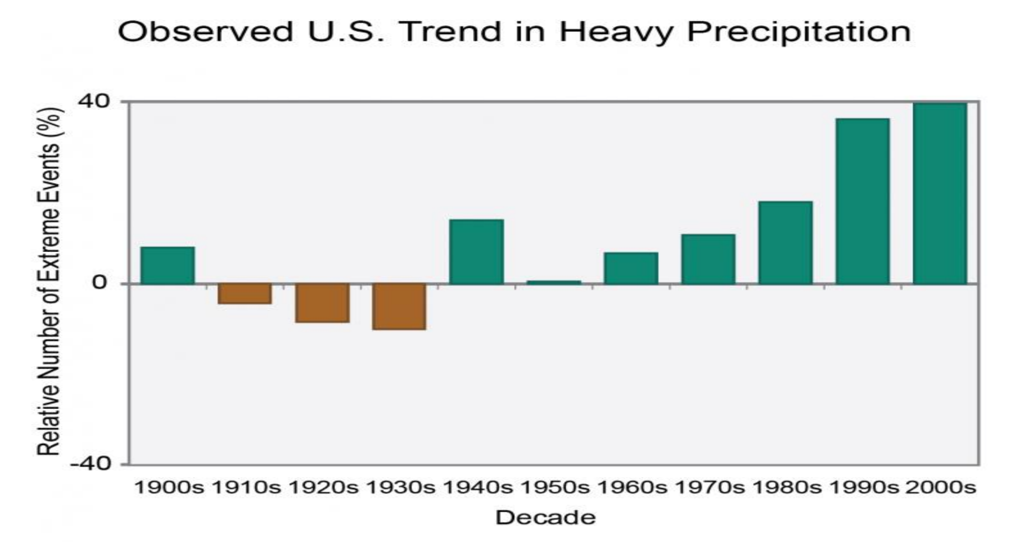


Figure 3.1: The observed U.S. trend of a 2-day precipitation that is exceeded once every five years. Heavy precipitation from 1901-2012 showing the occurrences of such events more common in recent decades compared to 1901-1960s. Largest increases in Northeast, Great Plains, Midwest, and Southeast. Source: (National Climate Assessment, 2021).

UNDRR (2002) indicates that extreme precipitation cause floods and drought that both have major socio-economic impacts globally, and some countries including United States experience both extremes at the same time. Floods are caused by too much precipitation while droughts are caused by prolonged deficit of precipitation. Even

though flood is the leading water-related disaster with greatest damages and deaths, severe droughts also continue to have serious impacts on some parts of the world leading to starvation and dependence on food aid. Severe drought affects over 37% of United States with longest time span in southeastern states (UNDRR, 2002) .

The extremes can be described as rare occurrences. Extreme climate event is defined as “the occurrence of a value of a variable above or below a threshold value near the upper or lower ends of the range of its observed values in a specific region.” The extreme climate includes severe rainfall, snowstorms, blizzards, cyclones, hurricanes, floods, droughts, and others (Institute of Medicine, 2008; NCBI, 2021). The extremes can be severe short -lived such as heavy precipitation, tropical cyclones, floods or long lived such as drought and heat waves (Stephenson et al., 2008). Floods results in massive damages and loss of life, properties, infrastructure. The prolonged drought leads to water shortages, marine ecosystem loss, crop and agriculture failure, illnesses, and mortality (Institute of Medicine, 2008; NCBI, 2021). Evaluating extreme precipitation is necessary to better understand their pattern and quantify their severity to aid with management, mitigation, predictions, and early warnings to achieve climate resilience, and reduce socioeconomic losses (Heim, 2015; WMO, 2021).

Snowfall is also an important type of precipitation in areas where their water resources is heavily depended on snowpack including some parts of United States (Knowles et al., 2006). However, the studies indicate that global warming reduces snowpack (Karl et al., 1993) causing a shift in runoff due to earlier snowmelt and Winter precipitation falling as rain instead of snow. The increase in runoff affects streamflow

and thus the timing and availability of water. Another study indicated a shift in snowfall and a decrease in snowfall and precipitation ratio (Feng & Hu, 2007).

The statisticians mainly focus on the center of the data, that is average (mean) to characterize typical behavior. However, the use of maximum and minimum values is appropriate especially when dealing with extremes. Trend analysis has been the main approach in assessing climate variability and change, however even though good, trend analysis detects general increase or decrease in trend of time series data. In-depth analysis is needed to understand and quantify climate extremes (Yilmaz et al., 2014). The commonly used methods for extreme rainfall are annual maxima and peak over threshold (POT) (Kunkel et al., 2013; Yilmaz et al., 2014) which both have their tradeoffs. In their study, (Yilmaz et al., 2014) used POT to construct extreme rainfall data. Extreme value is also commonly used in water resources engineering (Towler et al., 2010; Yilmaz et al., 2017). A simple but robust method is necessary for extreme analysis.

3.2. Objectives

The purpose of this study is to quantify the extreme climate (Very Wet and Very Dry) to evaluate how precipitation varies for individual years, seasons, and months in each climate. This is important because extremes result in major impact to society by causing floods and droughts.

Specific objectives are to:

1. Quantify inter and intra annual, seasonal, and monthly precipitation for extreme climate classification (Very Wet and Very Dry climate classifications)
2. Compare Very Wet and Very Dry climate classifications.

3.2. Methodology

3.2.1. Study area

The study was performed in the City of Sioux Falls, the largest city in South Dakota, USA. Sioux Falls is in Minnehaha County and extends into Lincoln County (Figure 3.2). Sioux Falls is in the Big Sioux River Valley in southeastern South Dakota, United States. It is located at 43.55^{o}N, 96.73^{o}W and lies 1421 feet above sea level. There is a diversion canal along Big Sioux River and Skunk Creek to reduce flooding at the airport during snow melt. The location of the weather station used in this study is at the airport FSO 397667 (Coop) located at 43.5778 degrees, -96.7539 degrees in between the Big Sioux River and the Diversion Canal. According to U.S. Census Bureau (USCB, 2018) Sioux Falls covers about 78.04 square miles of which 77.5 square miles is land and 0.53 square miles is water. The population was 183,793 as of 2019 census. The annual average temperature is 45.1 Fahrenheit (^{o}F) and averages with 14 ^{o}F in January, and 73 ^{o}F in July. The average annual precipitation is 24.69 inches of rain and 38.1 inches in snow.

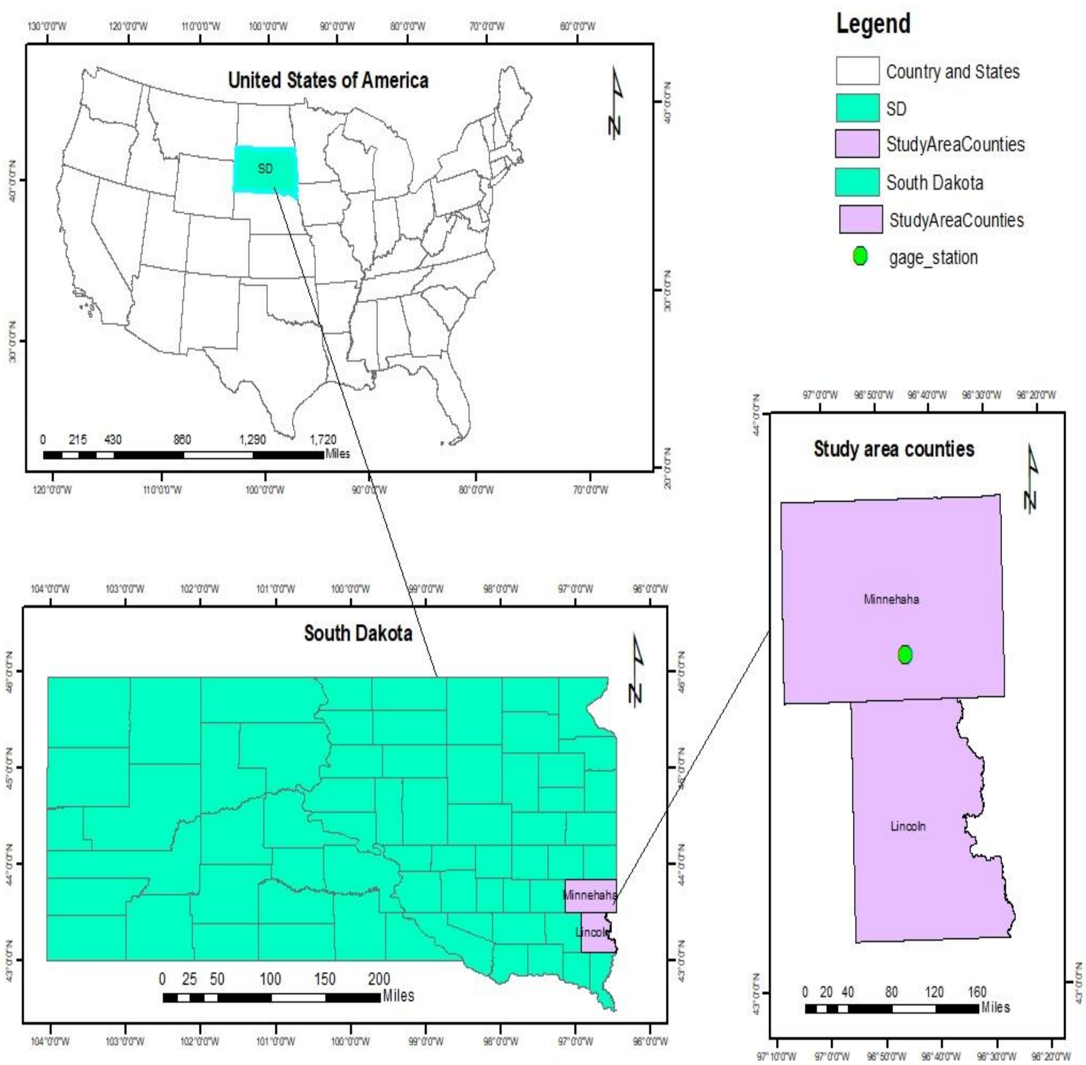


Figure 3.2. Location of study area and the gauge station in Minnehaha County

The land uses are residential and commercial areas, pastures, croplands, hayfields, forests, and farmlands (Chuang et al., 2011). Sioux Falls is under hydrologic subregion A which is described as Minnesota-Red River Lowland, Coteau des Prairies, and eastern part of the Southern Plateaus physical divisions of Flint (1955) (Sando, 1998). It is in

South East (SD09) climate division. The study area was selected based on the availability and quality of historical data to achieve the research goals, the climate variability concerns, and the development that results with increased runoff causing flooding.

Sioux Falls has a continental climate with four seasons, Fall, Winter, Spring, and Summer. The seasons range from warm or hot and humid Summers to cold and dry Winters (Atlas, 2020). July is the hottest month with many days with 90 ^{o}F to 100+ ^{o}F. Sioux Falls is susceptible to thunderstorms and tornadoes in late Spring and early Summers. January is coldest in Winter with temperatures below freezing with snowfall up to 8 (in). February is a chilly month with very cold nights and blizzards are common during this time. March gets frequent snowstorms, and it is the start of Spring season.

3.2.2. Data acquisition

The daily precipitation and snowfall for the years identified as Very Wet (6 years) and Very Dry (10 years) climate classifications from chapter two were acquired. These climate classifications were identified from 126 years of data from Sioux Falls Foss Field station which is the only station with the longest and consistent data. The daily data listing historical precipitation data (described as rain and liquid equivalence of snowfall (melted snowfall)) and snowfall (amount of snow that has fallen since the last observation) from Sioux Falls Foss Field weather station ID 397667 (Coop) was obtained from High Plains Regional Climate Center CLIMOD (HPRCC) (CLIMOD, 2020). The precipitation period of record in this station was 1893-01-01 -2020-01-05 when the data was obtained. Data had traces recorded as T: Trace amount less than 0.01" precipitation and less than 0.1" snowfall. The GIS data layers were acquired from Geospatial Data Gateway (USDA, 2020) to create study area maps.

3.2.3. Quality control

The quality control was performed to assess the quality of data and estimate the gaps. In this study, precipitation and snowfall data had traces and no missing data, quality control was performed to estimate traces. Traces are precipitation less than 0.01 (in) and snowfall less than 0.1 (in) that cannot be measured by gauges. The user decides on how to treat traces (Yang et al., 1999), therefore, 0.005 (in) was used to fill daily traces for precipitation and 0.05 (in) for snowfall. The Very Wet climate precipitation data had about 19.4 % of traces and snowfall data had about 9.6 % traces while the Very Dry climate had about 21 % of traces and snowfall data had about 11% traces. The Very Wet and Very Dry years daily data for each water year was assessed for precipitation and snowfall equal to zero, greater than zero, and traces. After estimating traces, data was summarized for total precipitation and total snowfall, that is precipitation greater than zero plus traces.

3.2.4. Data analysis

In Chapter two, precipitation data was classified as Very Wet, Wet, Average, Dry, and Very Dry climates from 125 years of data from 1985-2019 using parameters in Table 3.1. Here we analyze the Very Wet and Very Dry climate classifications, which are 6 and 10 years, respectively. Very Wet and Very Dry climate classifications were analyzed using the procedures as follows: First the daily precipitation and snowfall data for each water year in each climate classification was summarized for number of days with precipitation greater than zero, precipitation equal to zero, precipitation and snowfall equal to traces, and total precipitation (greater than zero including traces). The same

procedure was followed to summarize snowfall. The precipitation and snowfall days were the days with precipitation greater than zero which include estimated traces.

Table 3.1. Description of criteria used in classifying climate.

	Parameter	**Classification**
Above	Average + 1.5*Standard Deviation	Very Wet
Between	Average + 1.5*Standard Deviation & Average + 0.5*Standard Deviation	Wet
Between	Average + 0.5*Standard Deviation & Average - 0.5*Standard Deviation	Average
Between	Average - 0.5*Standard Deviation & Average - 1.5*Standard Deviation	Dry
Below	Average - 1.5*Standard Deviation	Very Dry

*indicates multiply, + indicates addition, and -indicates minus

The daily data was accumulated into monthly sums. Then the monthly data was aggregated into water year for annual analysis. The water year is a 12-month period that starts from October 1st of any given year to September 30th of the following year. The year that has many months (9 out of 12) is the water year, that is, 2019 water year is from October 1st, 2018, to September 30th, 2019 (USGS, 2019). Then intra and inter annual, seasonal, and monthly analysis were performed.

3.2.4.1: Annual analysis

The annual precipitation and snowfall and their % different from the overall average climate from 1895 to 2019 were analyzed. The annual precipitation and snowfall

and number of days with precipitation and snowfall were analyzed for precipitation and snowfall totals including trace amounts, and greater than trace amounts. The years were then analyzed and compared against each other within their respective climate and between Very Wet and Very Dry climate.

3.2.4.2: Seasonal analysis

For seasonal analysis, the monthly totals for each water year were converted to seasons by summing up the months according to water year to construct seasons as shown in Table 3.2. Seasonal analysis was performed on precipitation and snowfall and the days with precipitation and snowfall were analyzed and precipitation difference from the average seasonal climate. The seasonal precipitation and snowfall and number of days with precipitation and snowfall were analyzed for both precipitation and snowfall totals including trace amounts, and greater than trace amounts. Seasons were then analyzed and compared against each other within their respective climate and between Very Wet and Very Dry climate.

Table 3.2. Months in each season according to water year (USGS, 2019)

Seasons	**Months**
Fall	October-November-December
Winter	January-February-March
Spring	April-May-June
Summer	July-August-September

3.2.4.3: Monthly analysis

The monthly analysis was also performed by arranging data according to water year (Oct - Sep). The precipitation and snowfall, their differences from the average climate, and number of days with precipitation and snowfall were assessed. Monthly data was used to perform monthly analysis to compare monthly climate variability for all the years in their respective climate categories and between Very Wet and Very Dry climate.

The skew, average (mean), standard deviation, sum, maximum, minimum, percent difference, and CV were calculated for all months, seasons, and years. The results for two climate classifications were compared.

3.2.5. Statistical methods

The following statistical methods were used to analyze precipitation data.

3.2.5.1: Skewness

Skewness is a measure of the degree of asymmetry of a distribution. A normal distribution is symmetric about the mean with a bell-shaped frequency curve (Yamane, 1973). A distribution is skewed if the tail on one side of the distribution is longer than the tail on the other side. If the data is skewed in the direction of higher values, it is positive skewed, if it is skewed in lower values, it has a negative skewness. In a perfect distribution called symmetric, there is no skewness and the skew value will be zero (Freund et al., 1927). If the skewness is less than -1 or greater than 1, the distribution is highly skewed. If skewness is between -1 and -0. 5 or between 0.5 and 1, the distribution is moderately skewed. If skewness is between -0.5 and 0.5, the distribution is

approximately symmetrical (GoodData, 2019). The equation for skew function in excel is (Microsoft, 2021):

$$\frac{n}{(n-1)(n-2)}\sum\left(\frac{x_i-\mu}{\sigma}\right)^3 \quad (1)$$

Where n is number of values, μ is mean, x is observed value.

3.2.5.2. Average (Mean)

Mean is the sum of all observed values divided by number of values (Freund et al., 1927). It is commonly referred to as average. It is defined by:

$$\mu = \frac{1}{\mathrm{n}}\sum_{i=1}^{n} x_i \quad (2)$$

Where μ is mean, n is number of values, x is observed value.

3.2.5.3. Standard deviation

The standard deviation (σ) of a data set is the positive square root of its variance (Freund et al., 1927; Yamane, 1973). The variance of a data set is the measure of how much values in a dataset differ from their mean. It is the squared difference from the mean. The standard deviation is the calculation of how much a data set deviates from its mean. A low standard deviation indicates values tend to be closer to the mean (expected value) of the data set while high standard deviation indicates values are spread out over a wide range.

$$\sigma = \sqrt{\frac{\sum(x_i-\mu)^2}{n}} \quad (3)$$

Where σ is standard deviation, μ is mean, n is number of values, x is observed value.

3.2.4.4. Coefficient of variation

The coefficient of variation (CV) is the ratio of the standard deviation to the mean, expressed in percentage terms. It is a statistical measure of dispersion of data points in a data series around the mean. It is helpful in comparing the degree of variation from one data set to another. It does not tell much unless it is compared to the mean. For example, CV =10% is a smaller variation than CV = 100 (Freund et al., 1927). The lower the percentage, the less variation. It is defined as

$$CV = \frac{\sigma}{\mu}.100 \tag{4}$$

Where σ is standard deviation, μ is mean.

CV is used frequently in hydrology to provide an indication of interannual and seasonal variability of hydroclimatic conditions of region.

3.2.4.5. Percent Difference

Percent difference (% diff) is the change over time and measures how much something has changed. It is used to calculate the amount of change compared to initial value.

$$\%Diff = \left(\frac{(New\ value - Old\ value)}{Old\ Value}\right) * 100 \tag{5}$$

Where percent difference could not be calculated, the difference from the average in inches was used.

Skewness was used to understand the distribution of data. Mean and standard deviations were used to understand the data and its variation, distribution and to create climate classification. The coefficient of variation was used to determine which year, season and month was the most variable or different. Percent difference was used to quantify the increase or decrease from the average climate. Where percent difference could not be calculated due to zeros, the difference from the average in inches was used. The standard deviation and mean together provide good amount of information about the distribution of data even though they are only two descriptive measures (Freund et al., 1927).

3.3. Results

The study analyzed Very Wet and Very Dry climate classifications, which are extreme climates identified from 125 years of long-term historical precipitation data. The intra and inter annual, seasonal, and monthly precipitation and snowfall variability were analyzed and quantified.

3.3.1. Very Wet climate

3.3.1.1. Annual variability

The annual average precipitation and snowfall for Sioux Falls are 26 in and 38 in, respectively. The average annual number of days with precipitation is 90. Table 3.3 shows the summary of precipitation and snowfall data for Very Wet climate. Figure 3.3 shows the annual precipitation and snowfall for Very Wet climate compared to average climate. Precipitation is highest in 2010 (44 in) while snowfall total is highest in 1962 (82 in) while both were lowest in 1909, making 1909 the least Wet year in terms of precipitation and snowfall while 1962 is the wettest year in terms of snowfall and 2010 the wettest year in terms of precipitation (Figure 3.3). This could be due to the smaller number of days of precipitation and snowfall in 1909 compared to other years (Table 3.3), even though number of days do not correspond with total precipitation and snowfall in other years (Table 3.3). The annual precipitation and snowfall averages and standard deviation for Very Wet climate are 39 and 3.6 in (precipitation) and 62 and 11.9 in (snowfall).

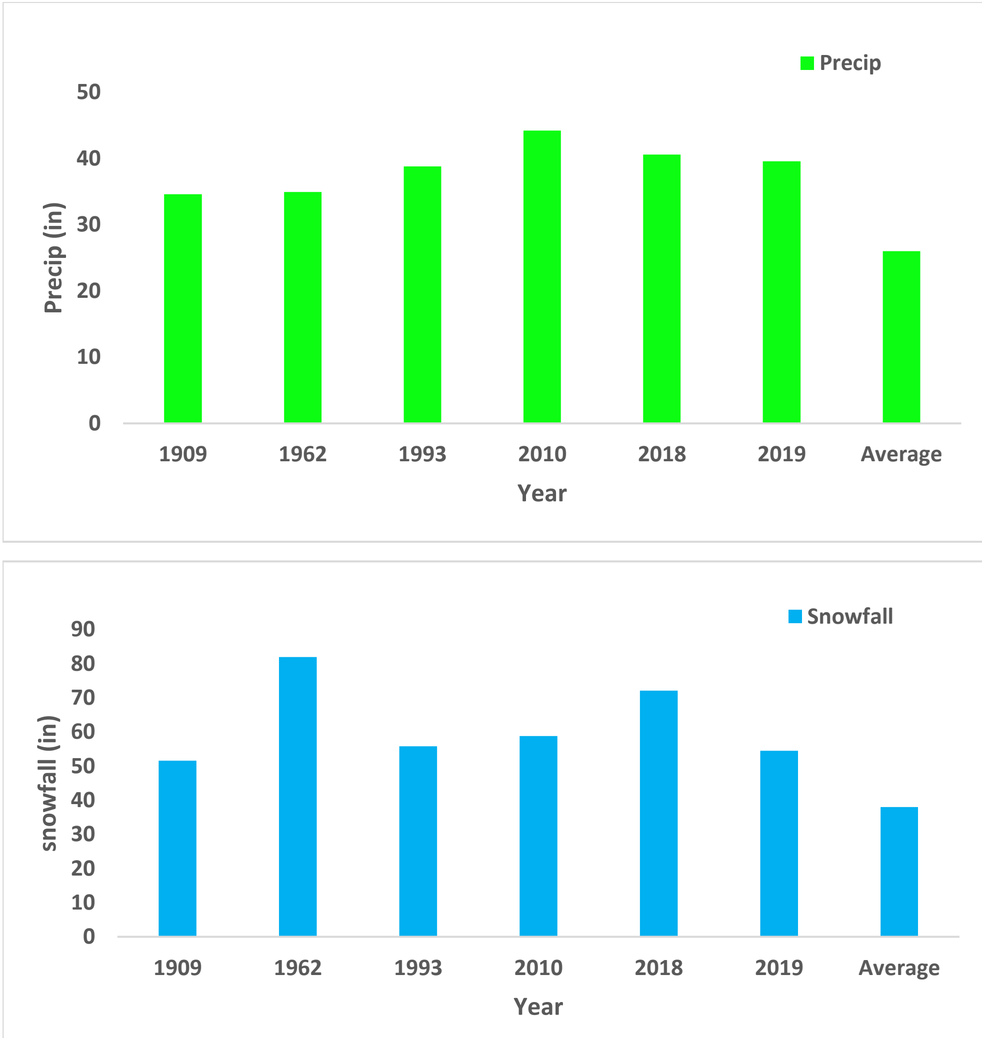


Figure 3.3. Annual precipitation and snowfall totals for the Very Wet climate compared to long-term average precipitation and snowfall (1895-2019)

The number of days with precipitation ranged from 33% in 1909 to 57% in 2019 and the number of days with snowfall ranged from 10% in 1909 to 24% in 1993 (Table 3.3). This indicates that 1909 received less precipitation and snowfall which corresponds with low number of days. However, precipitation and snowfall totals in other years do not correspond with number of days with precipitation or snowfall. This indicates that precipitation or snowfall totals are influenced by their intensities as some years have less

days with precipitation but have high precipitation and snowfall amounts in days that they have precipitation.

Table 3.3. Summary of days with precipitation and snowfall for Very Wet climate which are equal to zero (0), greater than zero (>0), trace (T), and total days with precipitation (>0 + traces). Highlighted in yellow are the minimums and highlighted in green are maximums.

Summary of data								
	% Days with precipitation				%Days with Snowfall			
year	0	>0	T	Total Precip Days	0	>0	T	Total Snowfall days
1909	67	17	15	33	90	4	6	10
1962	47	31	22	53	77	12	12	23
1993	44	31	25	56	76	10	14	24
2010	48	35	17	52	82	10	8	18
2018	55	28	17	45	81	10	9	19
2019	43	37	20	57	78	12	10	22

The differences from the overall average precipitation and snowfall (from 1895-2019) in Sioux Falls in Figure 3.4 show that precipitation difference is highest in 2010 with 70% increase and lowest in 1909 with 33% decrease in 1909 while snowfall percent difference is highest in 1962 with 116% increase from the average and lowest in 1909 with 34% increase. For Very Wet Climate, precipitation and snowfall show an increase from the average climate for all the years due to higher amounts of precipitation than average even though the increase differs for each year.

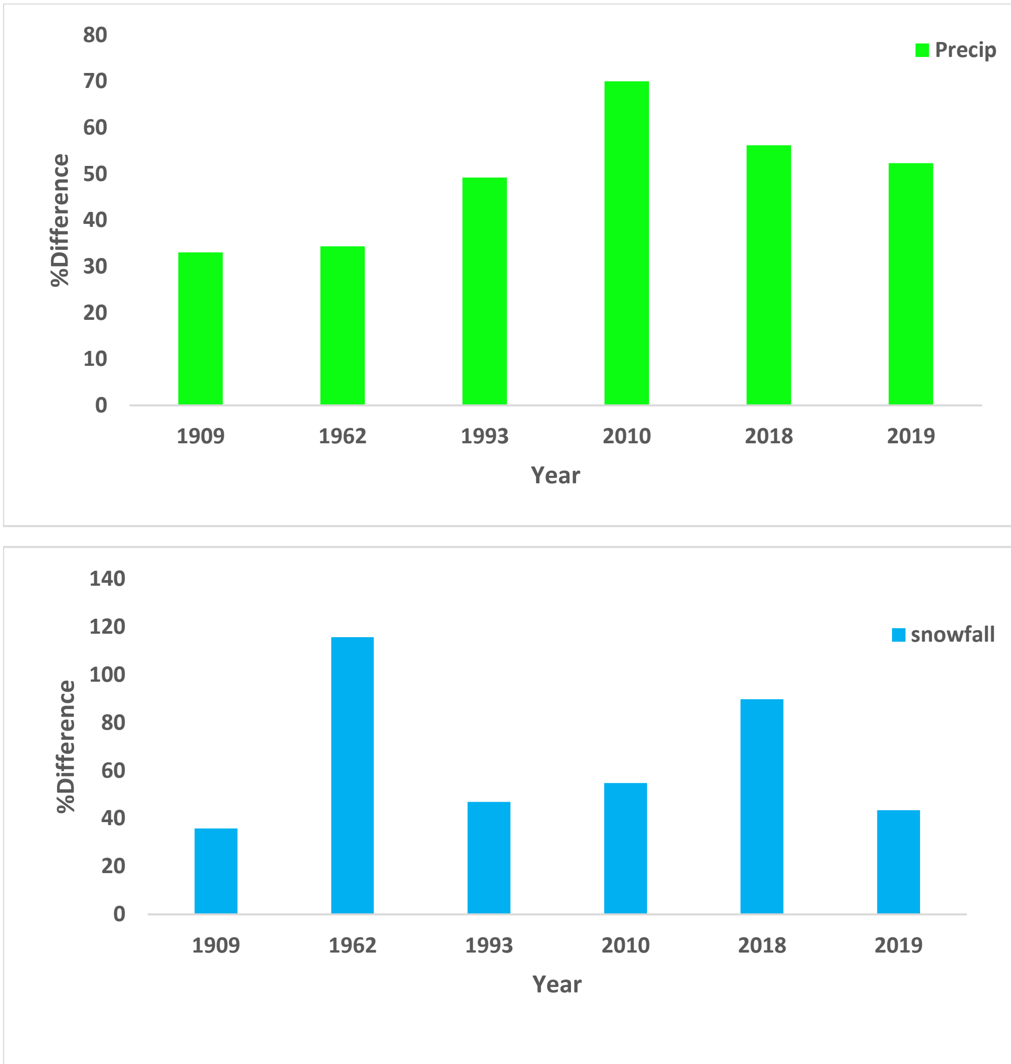


Figure 3.4. Annual precipitation and snowfall percent difference for Very Wet climate from the long-term average precipitation and snowfall.

3.3.1.2. Seasonal variability

The seasonal average precipitation for Sioux falls is 3.6, 2.8, 10.3, and 9.1 (in) for Fall, Winter, Spring, and Summer respectively, and average snowfall is 12.4, 22.4, 2.7, and 0 (in) for Fall, Winter, Spring and Summer, respectively. Figure 3.5 shows that for all the years, seasonal precipitation ranged from 3.6 in in the Winter 2010 to 19.4 in in the Summer in 2010. The precipitation is highest in the Spring for 1993 (17.7 in), 1909 (14.9 in), and 2019 (14.7 in) and highest in the Summer for 2010 (19.4 in), 2018 (17.6 in). The Fall has higher precipitation than Winter in 1993, 2010, and 2018, while 1909, 1962, and 2019 have higher precipitation in the Winter. Snowfall ranged from 0.1in in Summer to 68in in Winter. Snowfall is highest in the Winter except in 2018 which had the highest snowfall in the Spring (31.5 in) and 2010 has higher snowfall in the Fall than Winter (32 in). Generally, snowfall is highest in Winter, followed by Fall, Spring, and Summer with Very low to no snowfall. The presence of snowfall in the Summer and late Spring is due to traces could be from hail. Seasonal precipitation is above average for all the years while snowfall is below average in some seasons and years. Seasonal precipitation and snowfall for Very Wet Climate are higher than average precipitation and snowfall except for snowfall in the Spring as some years do not have snowfall in the Spring.

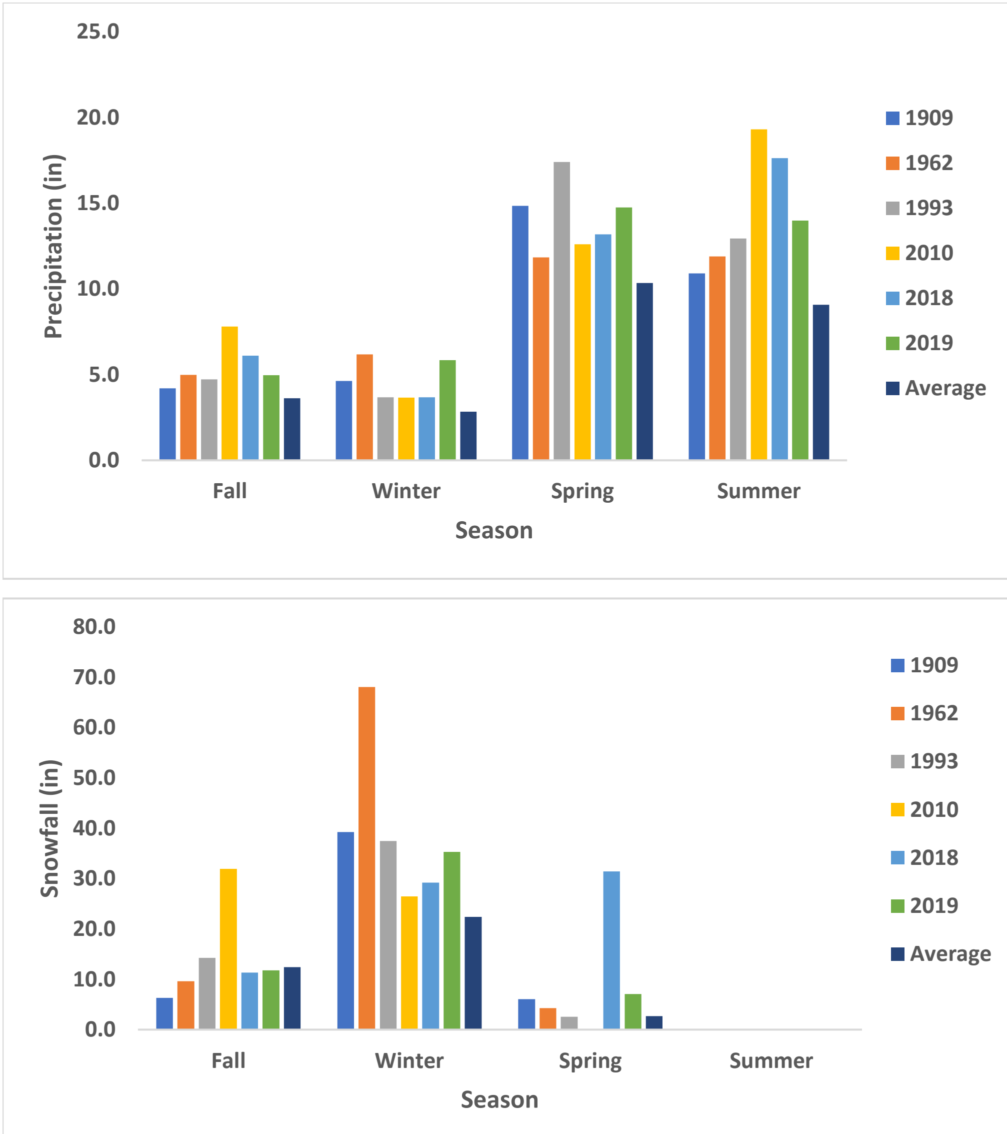


Figure 3.5. Seasonal precipitation and snowfall including trace amounts for Very Wet climate compared to long-term average seasonal climate.

Table 3.4: Seasonal number of days with total precipitation and snowfall (including traces 0.005 precipitation and 0.05 inches snowfall).

	Number of days with precipitation					
	1909	1962	1993	2010	2018	2019
Fall	22	42	46	51	38	44
Winter	24	57	47	46	42	48
Spring	38	55	59	51	48	65
Summer	35	39	52	42	37	50
	Number of days with snowfall					
	1909	1962	1993	2010	2018	2019
Fall	14	27	36	30	22	26
Winter	19	52	40	33	40	44
Spring	2	5	9	0	8	9
Summer	0	0	2	1	0	2

The seasonal number of days in Table 3.4 show that Spring has highest number of precipitation days followed by Summer and Winter and then Fall, except in 2010 where Fall has higher precipitation days than Winter and Summer. Winter in 1962 has highest number of days with precipitation than Spring. Snowfall has high number of days in the Winter followed by Fall, Spring and Summer with little to no snowfall. The presence of snowfall in the Summer is due to the trace amounts. Figure 3.6 and Table 3.5 show the decrease in precipitation and number of days with precipitation and decrease in snowfall and number of days with snowfall when precipitation and snowfall are greater than

traces. However, the seasonal pattern does not change for both precipitation and snowfall. There is low snowfall and number of days with snowfall in the Spring and no snowfall and no number of days with snowfall in the Summer. Generally, 1909 has lowest seasonal number of days with precipitation followed by 2018 while snowfall has low number of days in 1909 while other years vary with season.

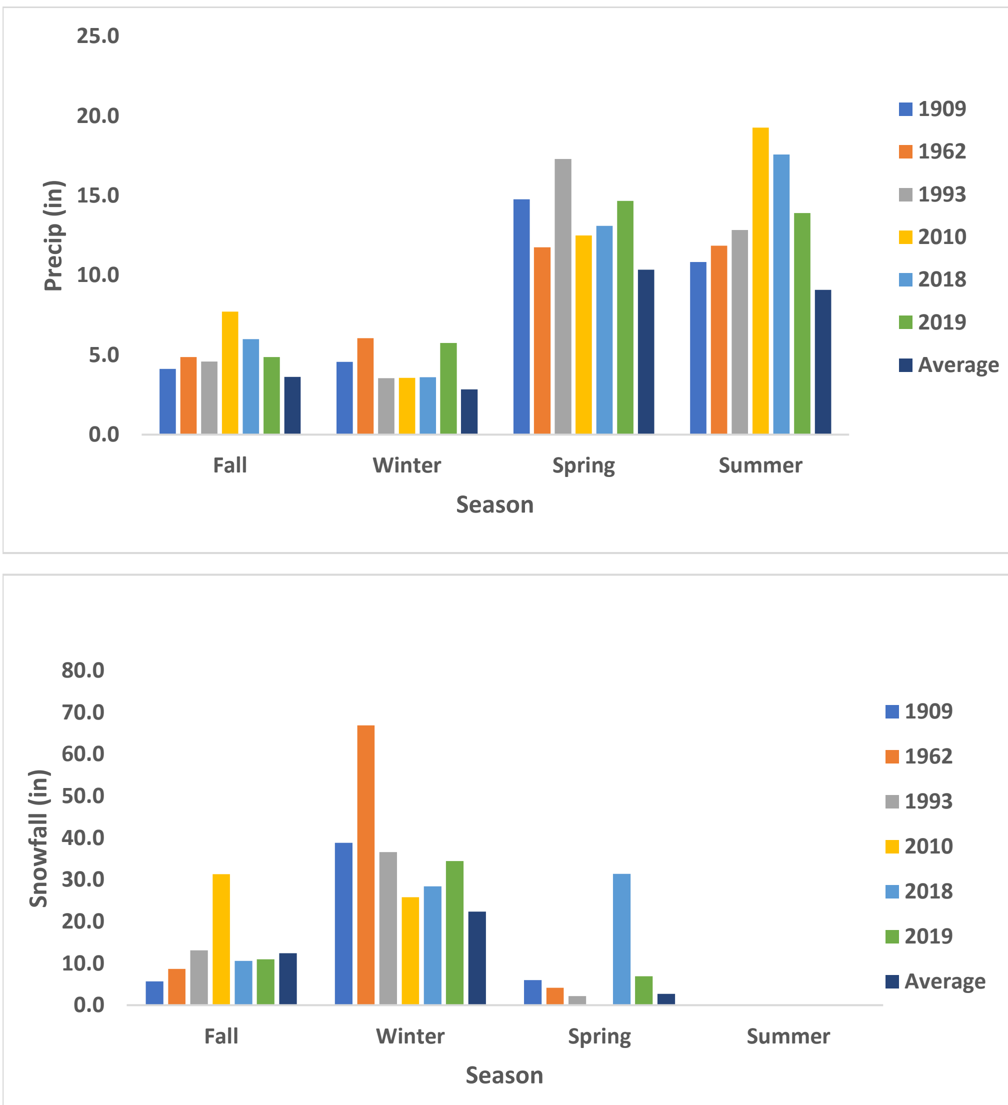


Figure 3.6: Seasonal precipitation greater than 0.01 and snowfall greater than 0.1 (that is greater than trace amounts) for Very Wet climate.

Table 3.5: Seasonal number of days with precipitation and snowfall greater than trace amounts (traces: 0.005 precipitation and 0.05 inches snowfall).

	Days with precipitation >than trace					
	1909	1962	1993	2010	2018	2019
Fall	8	18	20	35	16	23
Winter	10	31	23	26	25	31
Spring	24	36	37	33	32	47
Summer	21	29	32	33	30	34
	Days with snowfall >than trace					
	1909	1962	1993	2010	2018	2019
Fall	2	9	13	17	7	11
Winter	10	29	22	19	24	28
Spring	1	4	2	0	7	5
Summer	0	0	0	0	0	0

The precipitation difference from the average seasonal climate shown in Figure 3.7 show that Fall has highest increase in 2010 with 115.6% increase (4.2 in), followed by 2018 with 68.6% increase (2.5 in) and lowest in 1909 with 16.1%. Winter has highest increase in 1962 with 118.4% followed by 2019 with 106.2% increase and lowest in 2010 with 29.1% increase. Summer has highest increase in 2010 with 112.8% increase, followed by 2018 with 94.2% increase, and lowest in 1909 with 20.1%,

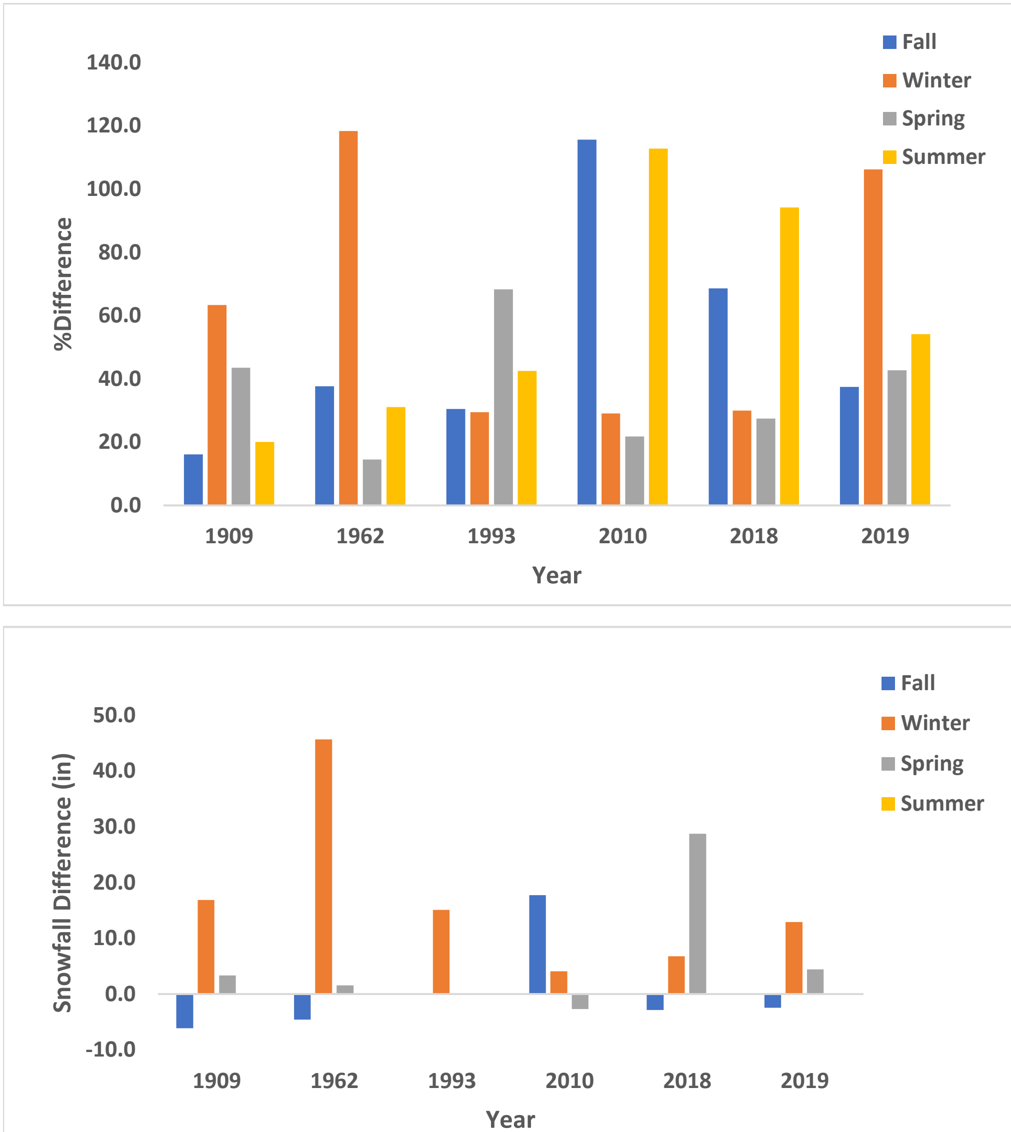


Figure 3.7: Seasonal precipitation percent difference for Very Wet climate from the overall average seasonal precipitation (1895-2019).

while Spring has highest difference in 1993 with 68.3% increase followed by 1909 with 43.5% (4.5 in increase) and lowest in 1962 with 14.5%. The snowfall % difference show more increase than decrease and the highest increase is in Winter 1962 with 45.7 in followed by Spring 2018 with 28.8 in and Fall with 17.8 in. The highest decrease is in

Fall 1909 with 6.1 in and lowest in the Spring 1993 with 0.2 in. No decrease in the Winter.

3.3.1.3. Monthly variability

Monthly precipitation ranged from 0.1 in. in November 2018 to 8.6 in. in July 2010 (Figure 3.8). Generally, November to March have low precipitation while May, June, and July have higher precipitation, even though August and September show higher precipitation in recent years (2018 and 2019). The years 2018 and 2019 have higher precipitation in October and from May to September while other years show higher precipitation starting in May. Monthly snowfall ranged from 0.1 to 48.8 in. in February. Summer months, which usually do not have snowfall records, show very low snowfall. The Fall also show low snowfall. The highest snowfall was recorded in February with 48.8 in. in 1962 followed by April 2018 with 31.5 in and December 2010 with 28.3 in. The year 1962 had the least number of months with snowfall among the Wet years, with just 6 months with snowfall starting from November to April, this indicates that the intensity of snowfall is more important than the frequency of snowfall as the amount influences the total annual amount of snowfall.

In general, monthly snowfall vary with year, February shows to have high amounts of snowfall; however December, January, March, and April also get high snowfall amounts with 2018 having highest snowfall in April (32 in), 2010 having highest in December (28.3 in), 1993 in March (15.2 in) while the rest of the years have highest snowfall in February.

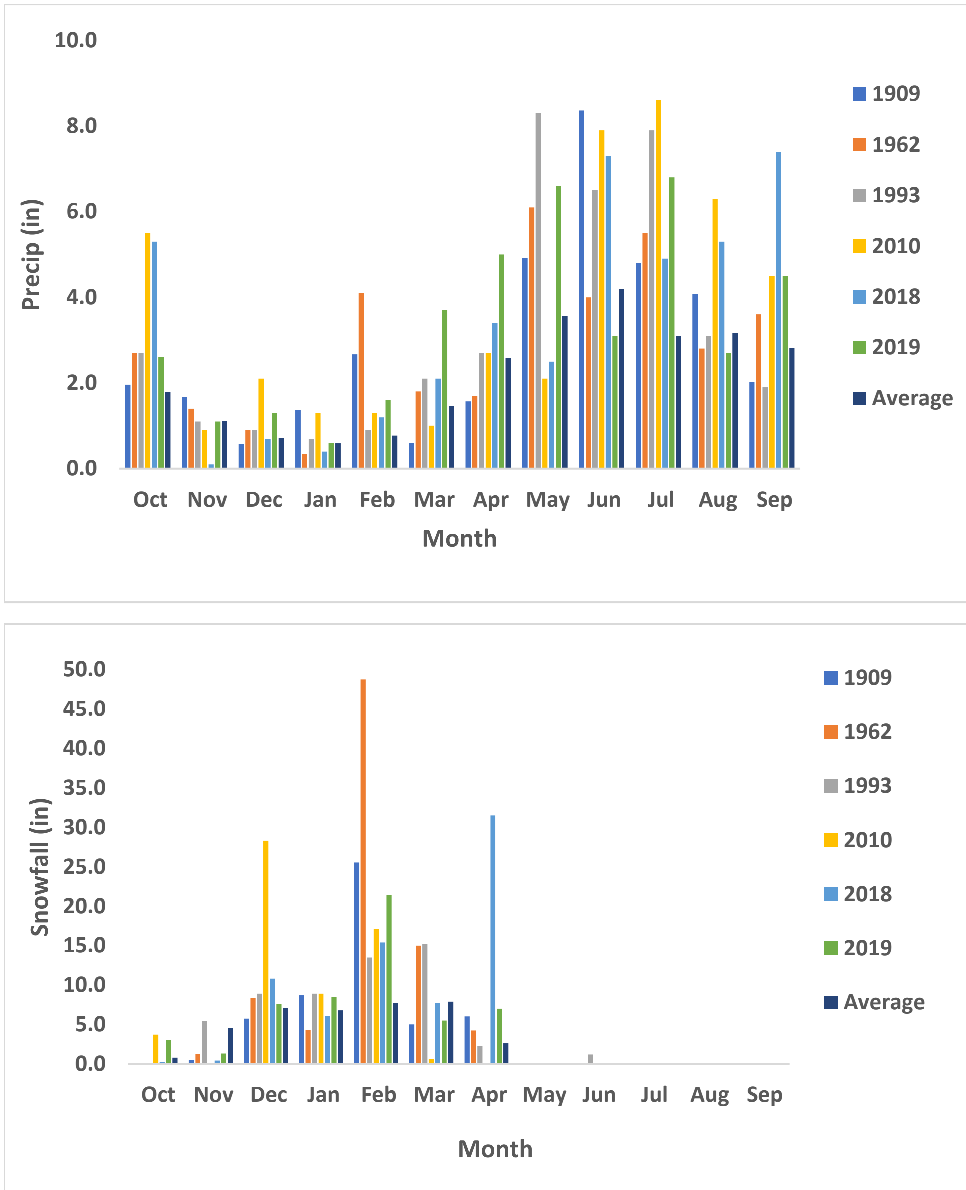


Figure 3.8: Monthly precipitation and snowfall (including trace amounts) for Very Wet climate.

The number of days with precipitation shows to be lower in March, August, and September, and higher in December, April to June, even though generally every month shows to have many days of precipitation (Figure 3.9). Precipitation days ranged from

5in in October 1909 to 25 days in April 2019. The number of snowfall days ranged from 0 in in June to September to 22 in December to February.

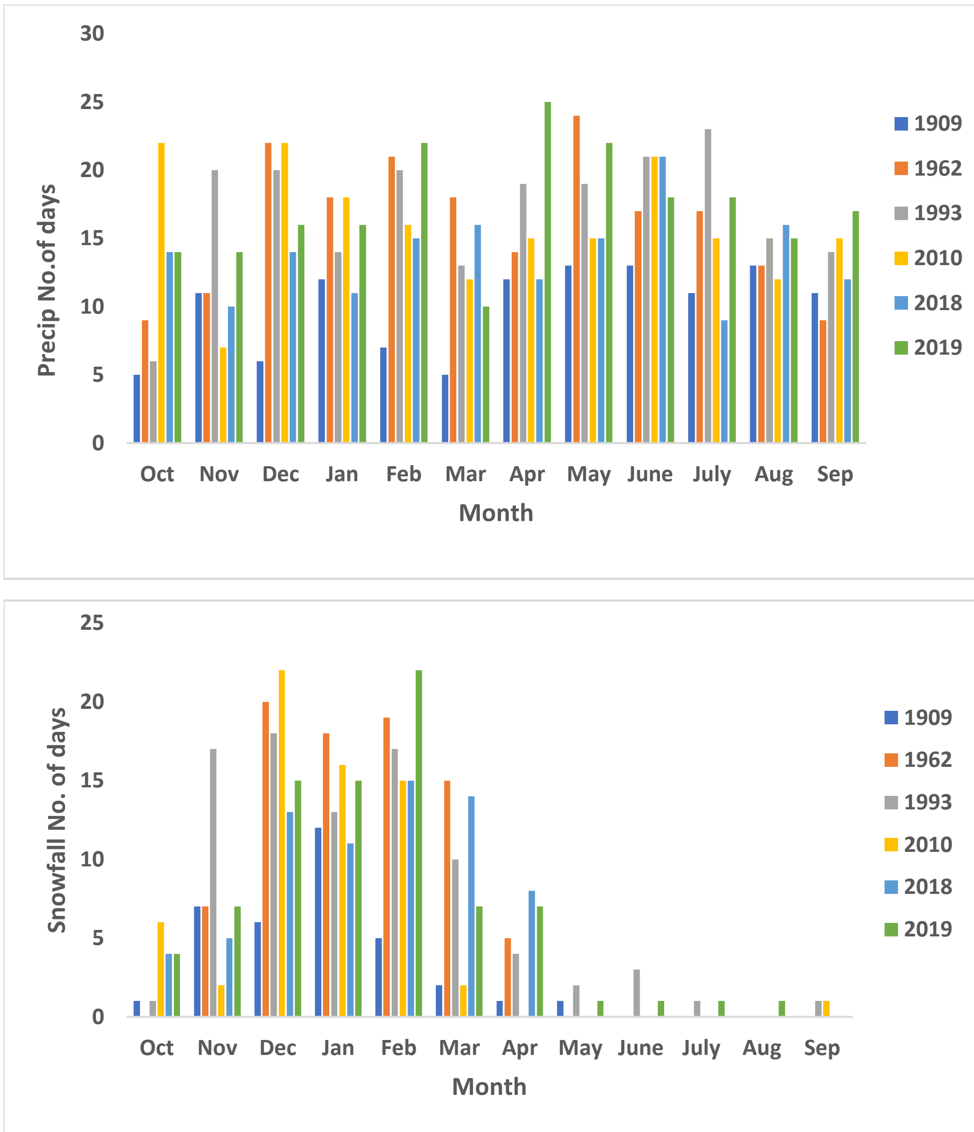


Figure 3.9: Monthly number of days for precipitation and snowfall for Very Wet climate for total precipitation and snowfall (including trace amounts).

The number of days is highest from December to February even though October to November and March to April still have moderate days with snowfall. May to

September also have a smaller number of days with snowfall, even though they are Spring and Summer months which is unusual to have snowfall during these times. This is due to the number of traces as evidenced by Figure 3.10 with precipitation and snowfall greater than trace amounts that show no snowfall from May to September.

Precipitation with no traces ranged from 0 in in November 2018 to 8.6 in in July 2010 showing 0.1 decrease in November with no traces and no difference in July 2010, meaning precipitation falling in July is greater than trace. Precipitation does not show much difference without trace amounts, with an average of 0.1 decrease in precipitation for November to March, while there is no difference from April to October. This means April to October are months with more precipitation greater than traces. However, the number of days with precipitation decreased with up to 8 days in some months when traces are excluded.

Snowfall ranged from 0 in to 48.4 in in February (1962), which is a 0.1 in decrease in November to 0.4 in difference in 1962. Snowfall shows a difference in the amounts of snowfall without traces of up to 0.6 in decrease and no snowfall in the Summer months (May to September). The number of days with snowfall in Figure 3.11 show a higher decrease in the number of days with snowfall of up to 7 days and no snowfall days from May to September.

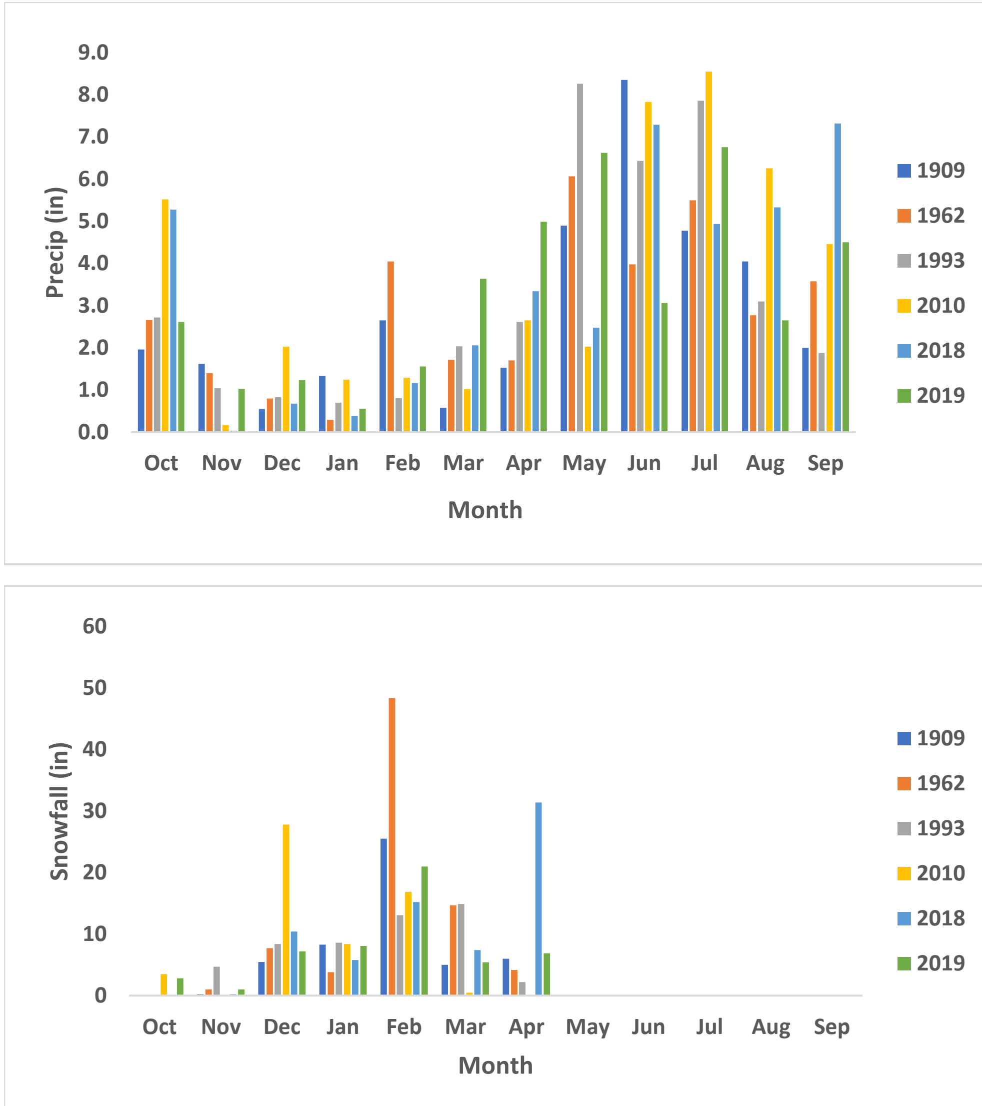
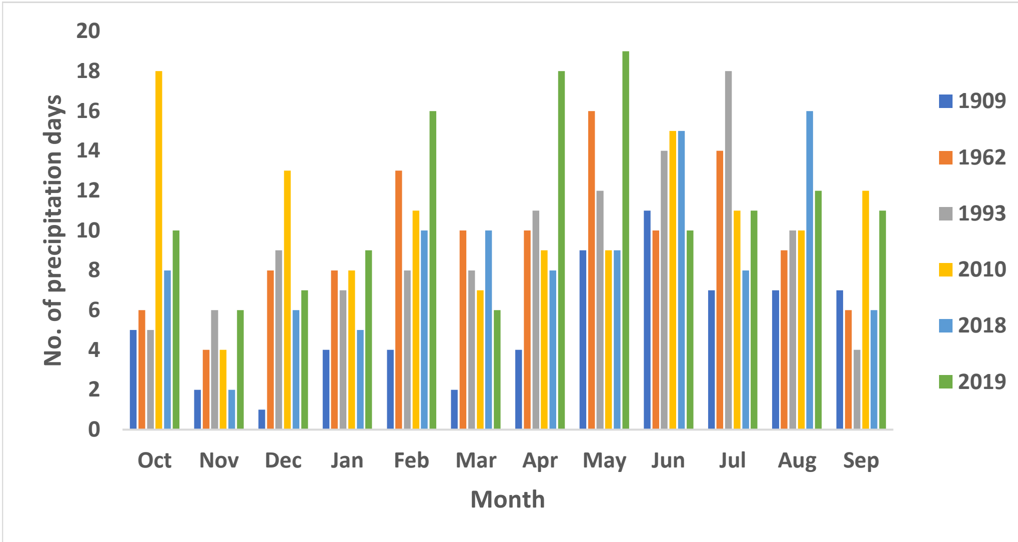


Figure 3.10: Monthly precipitation and snowfall greater than trace amount for Very Wet climate.



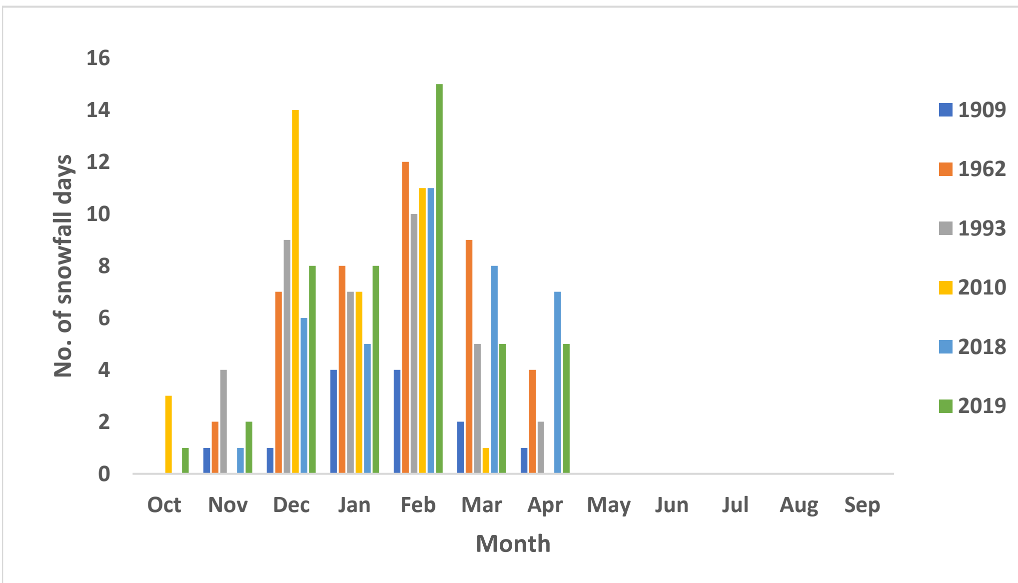


Figure 3.11: Monthly number of days with precipitation and snowfall greater than trace amount for Very Wet climate.

The difference from the average monthly precipitation shows to have high increase than decrease from the average (Figure 3.12). July has highest increase in 2010 with 5.5 in followed by May 1993 with 4.7 in, September 2018 with 4.6 in, June 1909 with 4.2 in, and October 2010 with 3.7 in. May has highest precipitation decrease of 1.5 in. in 2010,

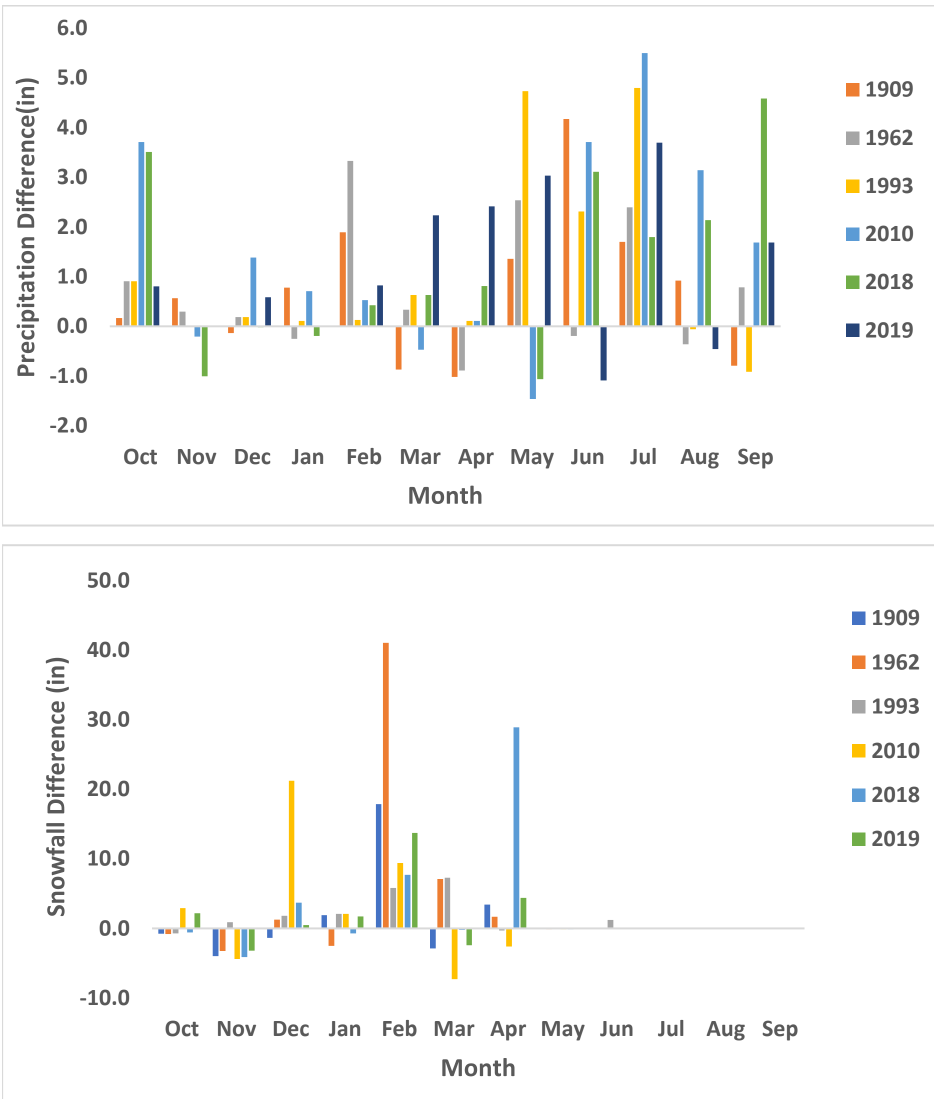


Figure 3.12: Monthly precipitation and snowfall difference for Very Wet climate from the overall average monthly precipitation for period of 1895-2019.

followed by 2018 in May and 2019 in June with 1.1 in and October in 2018 with 1.0 in and August (1993) and December (1909) has the lowest decrease with 0.1 in. Overall, the differences vary with months and years as each year has highest or lowest difference from average in different months.

Snowfall difference also shows high increase than decrease from average (Figure 3.12). The highest increase is in February 1962 with 41.1 in, followed by April 2018 with 28.9 in and December 2010 with 21.2 in while the highest decrease is in March 2010 with 7.3 in and lowest decrease in May with 0.1 in.

3.3.2. Very Dry climate

3.3.2.1. Annual variability

Annual precipitation (Figure 3.13) for Very Dry climate ranged from 13.5 in. in 1976 to 18.2 in. in 1955 and snowfall ranged from 10.3 in in 1987 to 43.4 in. in 1989. The average for Very Dry climate precipitation and snowfall is 17 in and 25.2 in with standard deviations of 1.4 and 12.2 in, respectively. Precipitation does not vary much from year to year even though 1976 shows to have lower amount (13.5 in), however, precipitation for Very Dry climate is less than the precipitation for the average climate (Figure 3.13). Unlike precipitation, snowfall highly varies from year to year with the lowest in 1987 with 10 in and highest with 43.4 in which is about 33 in difference. The snowfall for Very Dry climate is lower than average climate except in 1989 with 43 in and 1976 amount is equal to average climate.

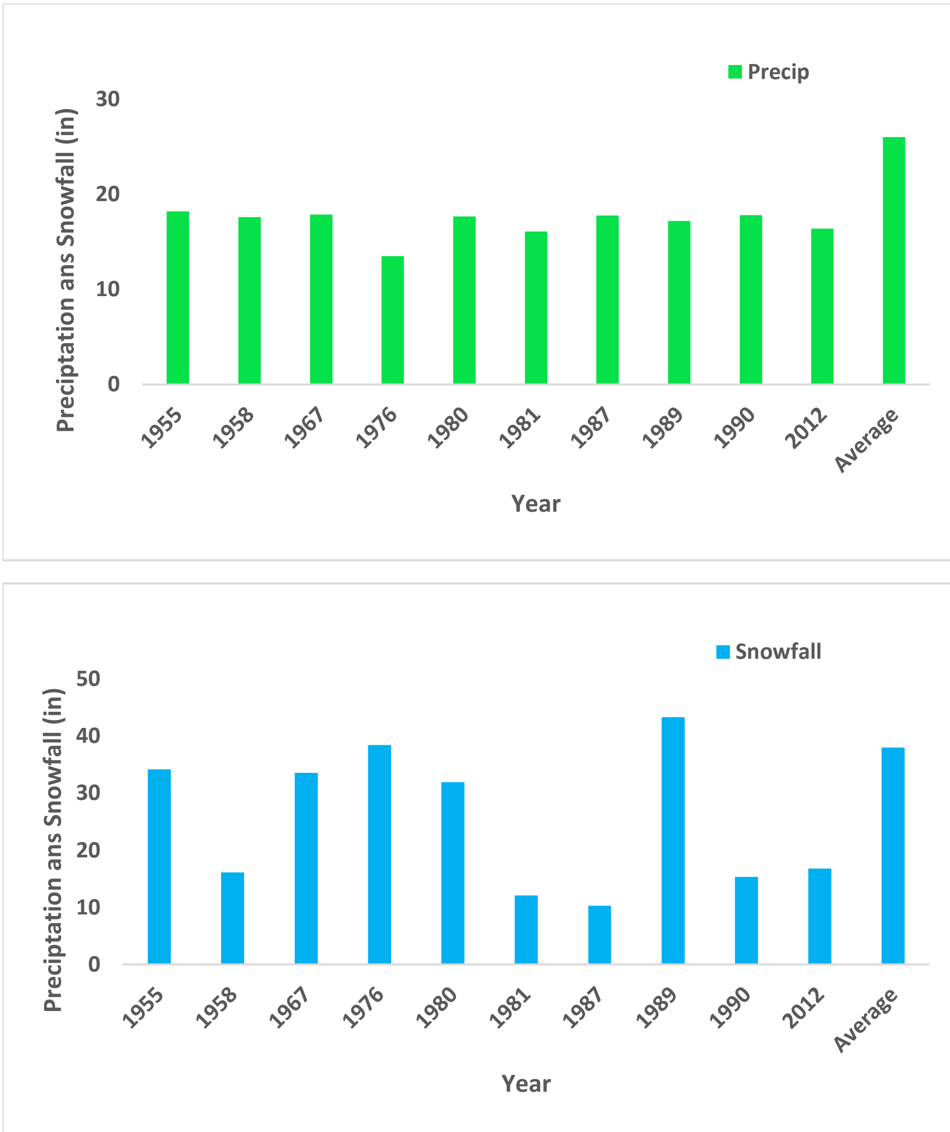


Figure 3.13: Annual precipitation and snowfall including trace amounts for Very Dry climate compared to average climate from 1985-2019.

The CV for all is 8% for precipitation and 46% for snowfall, meaning precipitation does not vary much from their mean. The number of days with precipitation is highest in 1967 with 52% and lowest in 2012 with 36% while the number of days with snowfall is highest in 1955 with 22 % and lowest in 2012 with 11% (Table 3.6). This shows that the number of days with precipitation or snowfall do not correspond with

precipitation or snowfall amounts. 48 to 64% of days have precipitation equal to zero while ones greater than zero is from 21 to 27% and trace precipitation is from 15% (2012) to 28% (1955 and 1967). While snowfall days equal to zero range from 78 (1955,1967, 1980) to 89% (1981, 2012), greater than zero range from 3 (1987) to 10% (1989), and equal to trace range from 5 (2012) to 15% (1955, 1958, 1967). This shows that days with snowfall greater than zero are the lowest.

Table 3.6: Summary of days with precipitation and snowfall for Very Wet climate which are equal to zero, greater than zero, equal to trace (T), and total days with precipitation(>0 + traces).

% Days with precipitation					**%Days with Snowfall**			
Year	0	>0	T	Total precip days	0	>0	T	Total Snowfall days
1955	52	21	28	48	78	7	15	22
1958	55	21	24	45	81	4	15	19
1967	48	24	28	52	78	7	15	22
1976	64	20	16	36	84	7	9	16
1980	49	25	25	51	78	9	12	22
1981	58	23	19	42	89	4	7	11
1987	56	24	19	44	85	3	12	15
1989	58	26	16	42	81	10	8	19
1990	53	27	20	47	83	5	12	17
2012	64	21	15	36	89	6	5	11

The deviation from the long-term average precipitation is lowest in 1955 with -7.8 in (30% decrease) and snowfall in 1976 with 0.4 in (1% increase) which is the increase from average, meaning higher than average snowfall (Figure 3.14). The highest deviation

from average is in 1976 for precipitation with -12.5 in (48% decrease) and in 1987 for snowfall with -27.7 in (73% decrease). All precipitation shows a decrease from the average while Snowfall show increase in 1976 with 0.4 in and 1989 with 5.3 in, meaning snowfall in these years is higher than average climate.

Figure 3.14. Annual precipitation and snowfall percent differences from the average climate for Very Dry climate.

3.3.2.2. Seasonal variability

The seasonal precipitation and snowfall for the Very Dry climate ranged from 1.4 in. in the Fall in 1990 to 10.8 in in the Spring in 1990 for precipitation and 0.1 in. in the Spring and Summer (1955, 1980, 1987) to 28.8 in. in the Winter in 1989 (Figure 3.15). The average seasonal precipitation ranged from 2.6 in. in the Fall to 6.7 in. in the Spring

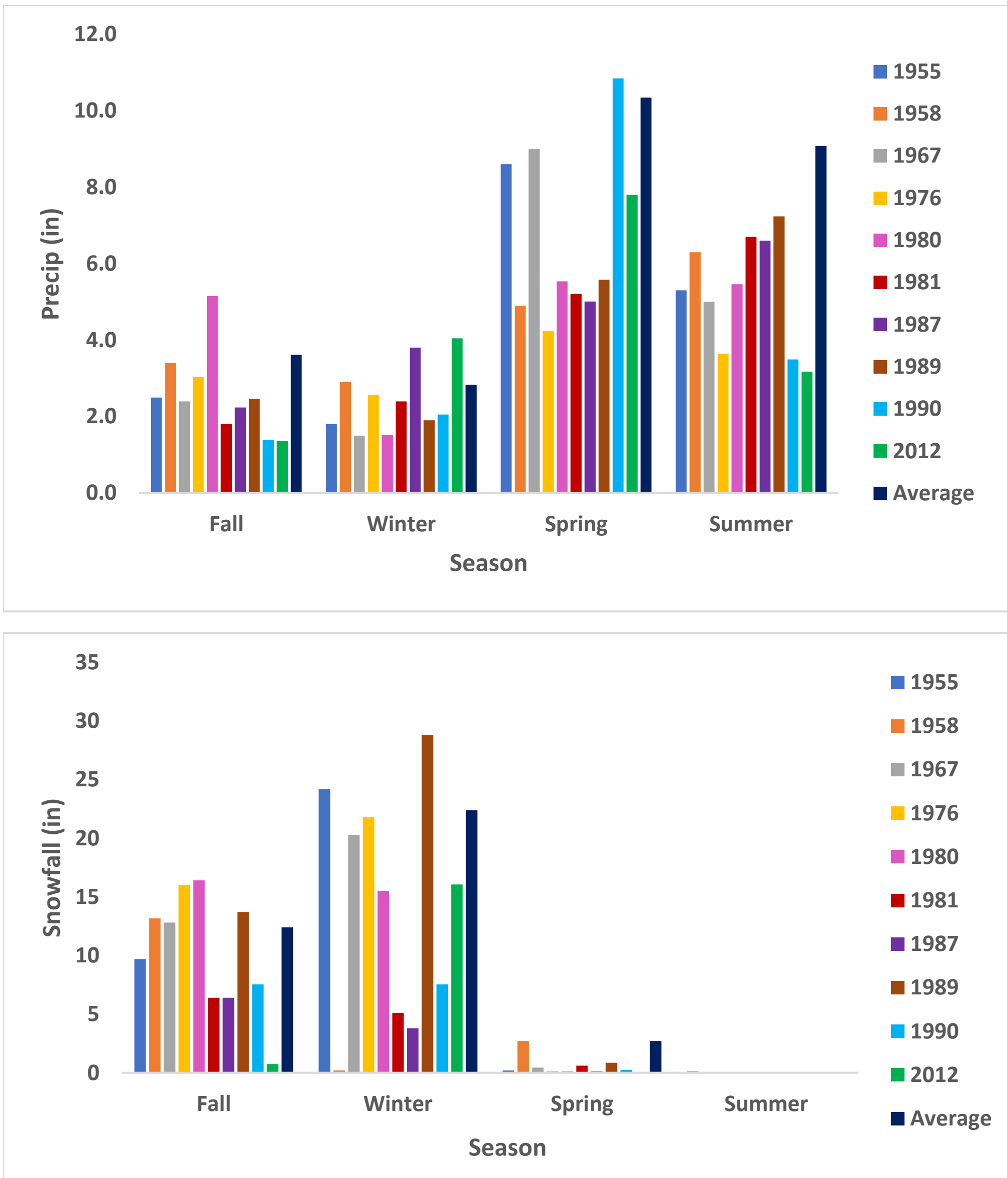


Figure 3.15. Seasonal total precipitation and snowfall including trace amounts for Very Dry climate from 1895-2019.

and the snowfall averages ranged from 0.1 in. in the Summer to 14.3 in. in the Winter. Seasonal precipitation and snowfall vary with each year as some years have highest precipitation in the Spring and some in the Summer while some years have highest snowfall in the Winter, and some have highest snowfall in the Fall and some in the Spring. Generally, Spring has highest precipitation followed by Summer, Fall and Winter. Winter has highest snowfall followed by Fall, Spring, and Summer with less or no snowfall. Most of precipitation is below average except in Spring 1990 with 10.8 in, Winter in 2012, 1987, and 1958 with 4, 3.8, and 2.9 (in) respectively, and Fall in 1980 with 5.2 in. Snowfall shows to be below average in some seasons and years and above average in some years and seasons except Spring shows to be below average.

Table 3.7. Seasonal number of days with total precipitation and snowfall (including traces: 0.005 precipitation and 0.05 inches snowfall) for Very Dry Climate.

	Number of days with precipitation									
Season	1955	1958	1967	1976	1980	1981	1987	1989	1990	2012
Fall	43	42	32	38	38	32	40	36	43	25
Winter	56	42	58	40	58	31	41	44	38	40
Spring	38	42	59	31	37	54	37	41	50	40
Summer	40	39	39	23	52	36	41	31	41	26
	Number of days with snowfall									
Season	1955	1958	1967	1976	1980	1981	1987	1989	1990	2012
Fall	21	41	23	27	26	17	23	26	32	9
Winter	54	4	48	31	51	20	30	37	25	30
Spring	4	23	8	2	2	3	2	5	5	0
Summer	2	0	0	0	0	0	0	0	0	0

The seasonal number of days with precipitation ranged from 23 in the Summer in 1976 to 59 in the Spring in 1967 (Table 3.7). On average, Winter has highest number of precipitation days, followed by Spring, Summer and Fall. Snowfall days ranged from 2 days in the Summer to 54 days in the Winter. On average, Winter has a greater number of days followed by Fall, Spring, and Summer. The presence of many traces in the Winter

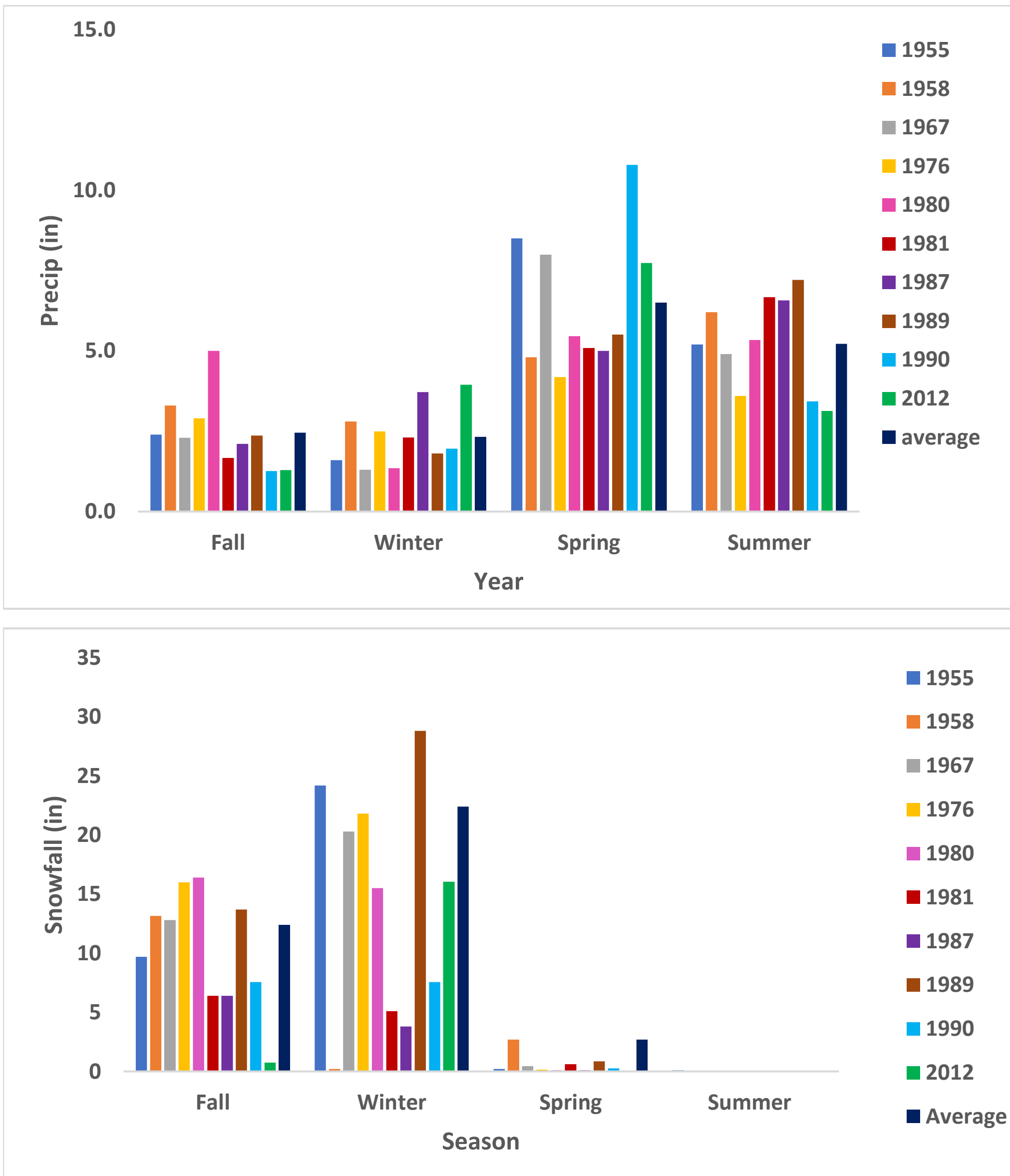


Figure 3.16. Seasonal precipitation and snowfall greater than trace amounts for Very Dry climate from 1895-2019.

may be the reason for highest precipitation days as precipitation days should be Very low in the Winter and high in the Summer and Spring. Also, snowfall days should not be present in the Summer. When traces are excluded, Figure 3.16 and Table 3.8 show that seasonal precipitation and snowfall amounts decrease slightly while their number of days greatly decrease ranging from 11 days in the Fall to 39 days in the Spring for precipitation and 1 day in the Spring to 25 days in the Winter for snowfall.

Snowfall decreases in the Spring and no snowfall in the Summer (Figure 3.16). The Snowfall amounts and days are highest in Winter followed by Fall and lowest in the Spring while precipitation is highest in the Summer and Spring followed by Fall, and lowest in the Winter (Table 3.8) compared to Table 3.7.

Table 3.8. Seasonal number of days with precipitation and snowfall greater than traces: 0.005 precipitation and 0.05 inches snowfall for Very Dry climate.

		Number of days with precipitation								
	1955	1958	1967	1976	1980	1981	1987	1989	1990	2012
Fall	17	18	11	17	19	11	14	17	16	12
Winter	20	12	21	23	24	15	23	26	19	21
Spring	22	24	34	21	22	29	24	27	39	28
Summer	17	23	21	14	28	29	27	25	25	17
	Number of days with Snowfall									
	1955	1958	1967	1976	1980	1981	1987	1989	1990	2012
Fall	5	3	7	11	9	5	3	14	9	4
Winter	22	10	18	15	25	8	8	21	8	17
Spring			1	1		1		2		
Summer										

The percent precipitation difference from average in Figure 3.17 shows that % difference differ with years and seasons. Some years and seasons have smaller differences from the average climate while others have larger differences from the average. Seasonal precipitation difference shows more decrease from the average except Spring 1958 which shows an increase of 35.4%, Fall shows an increase of 42.5% in 1980, and Winter shows an increase of 34 and 42.7% in 1987 and 2012, respectively.

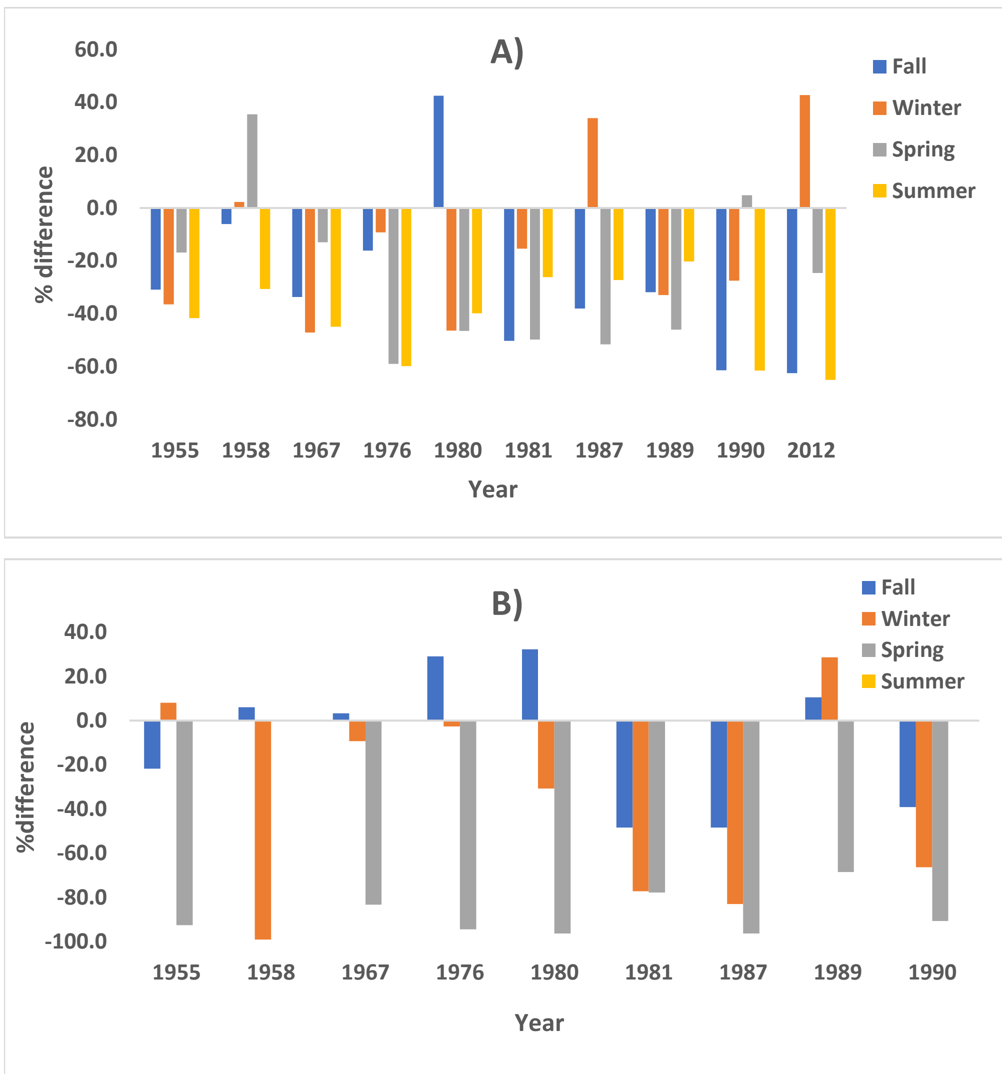


Figure 3.17. Very Dry climate seasonal precipitation (including traces) (A) and snowfall (B) percent difference from overall average climate from 1895-2019.

This shows that these seasons in these years had higher precipitation than the average seasonal precipitation. The highest decrease is in the Summer 2012 with 65% followed by Fall in 2012 with 62.5%, then Spring with 59% in 1976 and Winter with 47.1% in 1967.

Snowfall % difference from average climate is highest in the Winter 1958 with a decrease of 99.1%. The rest of the years show high decrease in Spring showing decrease from 96.3% in 1980 and 1987, 94.4% in 1976, 92.6% in 1955, 90.7% in 1990 and 83.3% in 1967. The lowest decrease is in Winter 1976 with 2.7% and 1967 with 9.4%. Fall and Winter show an increase in some years. The highest increase is in the fall 1980 with 32.2% and in Winter 1989 with 28.6% while the lowest increase is in the Fall 1967 with 3.2% and Winter 1955 with 8%.

3.3.2.3. Monthly variability

Precipitation ranged from 0.1 in. in October 1989,1990, November 1981, 2012, December 1980, 1987, and January 1958, 1990, to 4.9 in. in June 1990 (Figure 3.18). Monthly precipitation in Figure 3.18 show that precipitation is lowest in December, January, and highest in June. Generally, May, June, and July have higher precipitation even though April, August, and September show higher amounts in some years. October and March also have higher amount with 3.3 in. in 1980 and 1987. While October, November, December, January, February, and March generally have lower precipitation.

Monthly snowfall ranged from 0 in. in October, and April, to September for most of the years to 16.2 in. in March 1989. Generally, snowfall is high in November (up to 15.6 in), February (13.1 in), and March (16.2 in) and lowest from April to October. In

general, monthly snowfall vary with year, November, February, and March shows to have high amounts of snowfall. Low snowfall amounts in the Spring (May, June) and Summer (July, August, September) are due to trace amounts that could be due to hail.

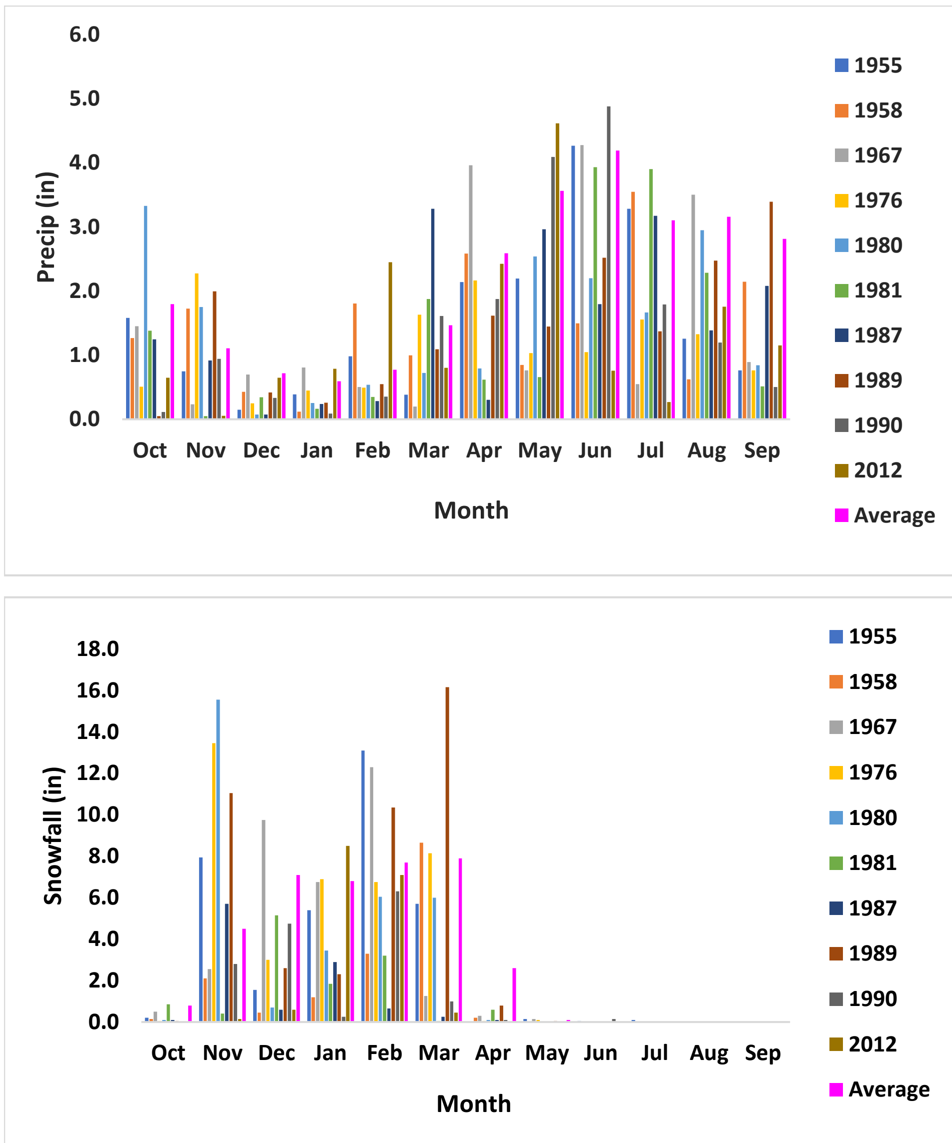


Figure 3.18. Monthly total precipitation and snowfall including trace amounts for Very Dry climate.

The number of days with precipitation range from 4 to 24 days (Figure 3.19). Every month show to have many days with precipitation even though years differ. The number of days with precipitation are many in the Winter months due to a lot of trace precipitation. This is shown in Figure 3.20 and 3.21 that show precipitation and number of days with precipitation greater than trace amount.

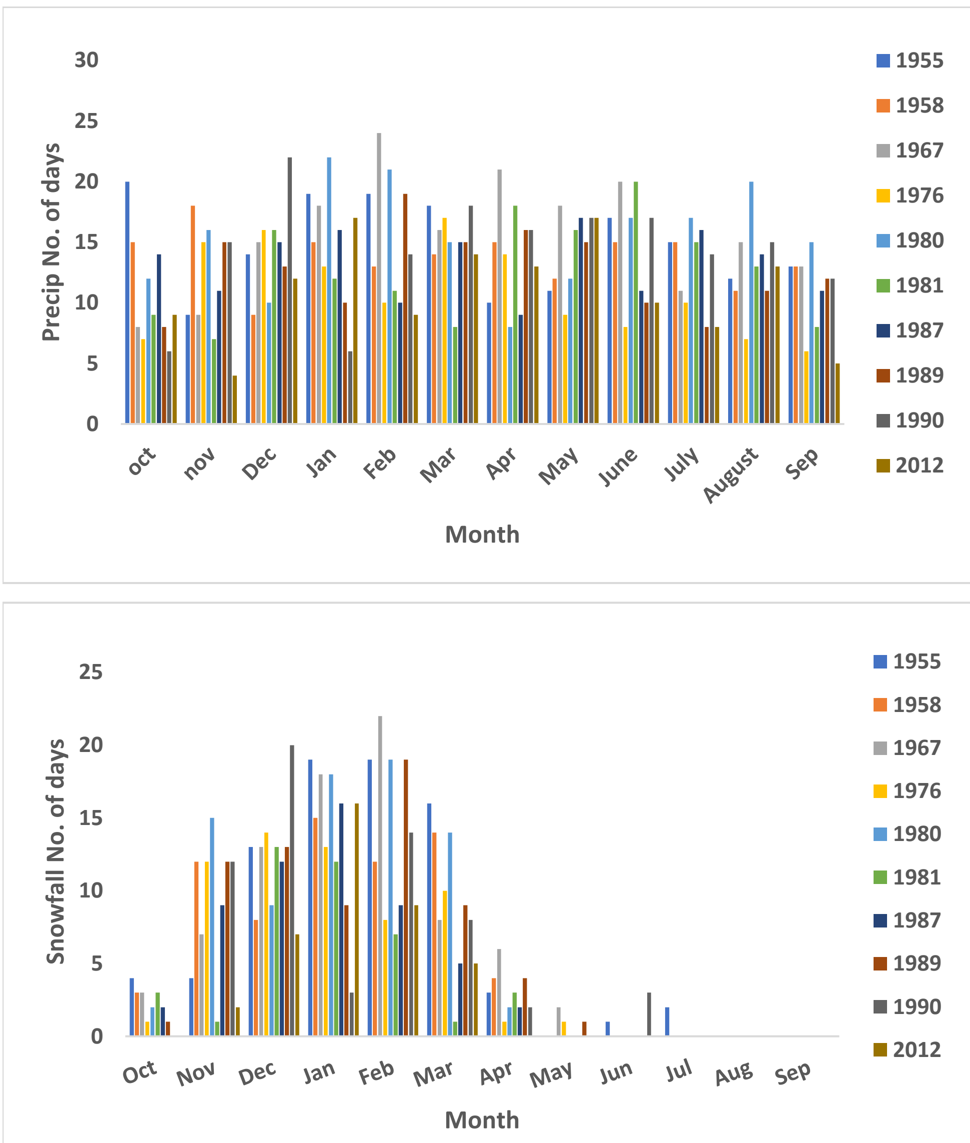


Figure 3.19: Monthly number of days with total precipitation and snowfall including traces for Very Dry climate.

The number of days with precipitation is reduced in the Winter months when traces are excluded and the number of days with precipitation are highest from March to August, with the highest in June 1967 with 17 days followed by August 1980 and May 2012 with 14 days.

The number of days with precipitation is generally low in December and January while lowest days are in November even though November has some years with high and very low number of days with precipitation. The presence of precipitation days in the winter months when temperatures are freezing could be due to liquid equivalence of solid precipitation. Even though the number of days with precipitation are reduced with only precipitation greater than trace amounts, precipitation amounts in Figure 3.20 show little to no change with the highest in June with 4.9 in, equal to the highest in Figure 3.18 and the rest of the months show similar amounts and patterns. This indicates that trace precipitation does not contribute much to total precipitation even though the number of days with precipitation does show a high difference.

The number of days with snowfall is high from November to March and the highest is in February with 22 days while the lowest is from April to October. Figure 3.20 show that the amount of snowfall is slightly reduced in some months with up to 0.5 in when trace snowfall is excluded and there is no snowfall from May to September, which are Spring and summer which usually do not get snow. The number of days with snowfall however reduced greatly with up to 19 days decrease in March 1967 and 18 days in January 1990. Reduced days with snowfall in October and April and May and no days

with snowfall in June to September. This shows that the warmer months get mostly trace amounts of snowfall.

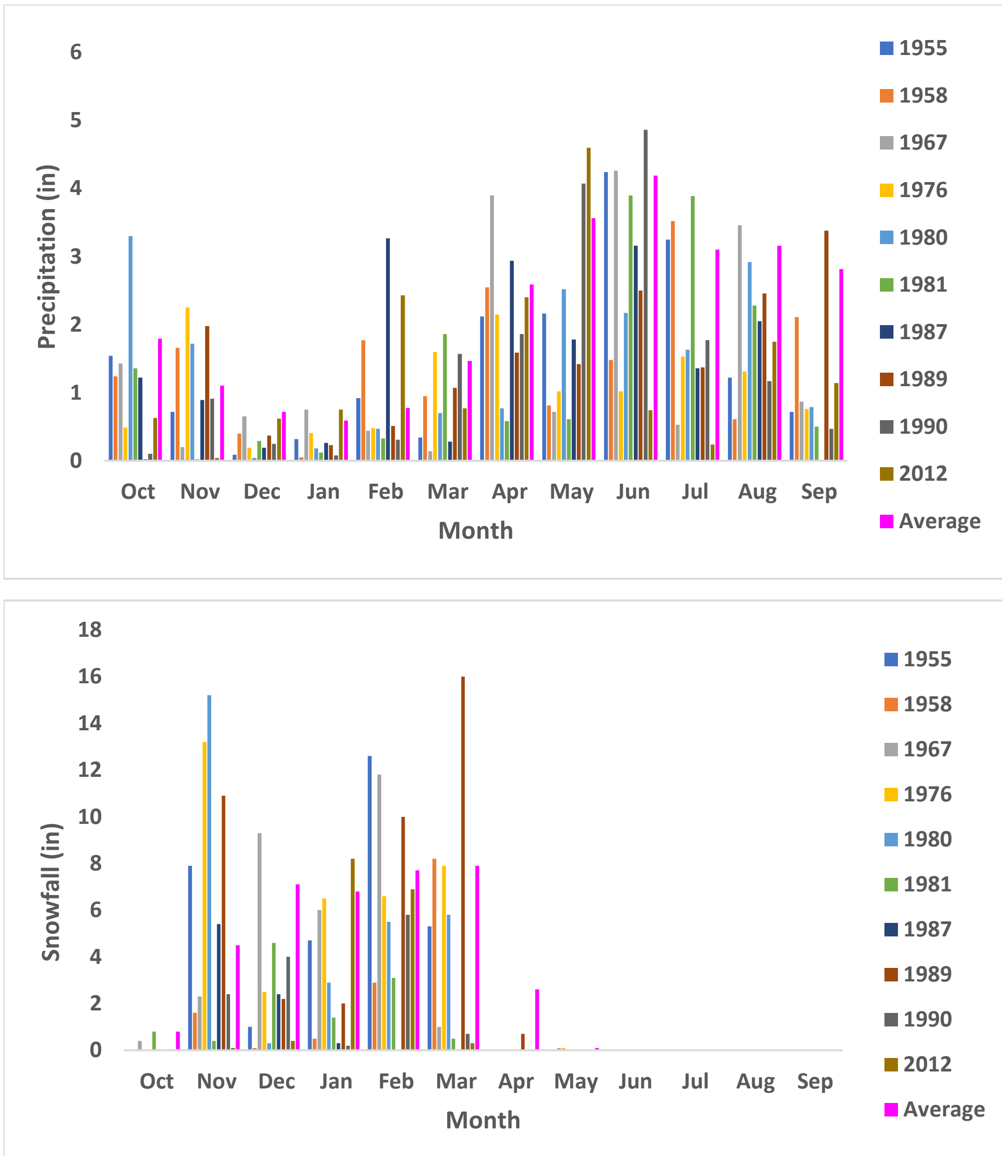


Figure 3.20. Monthly precipitation and snowfall greater than trace amount for Very Dry climate.

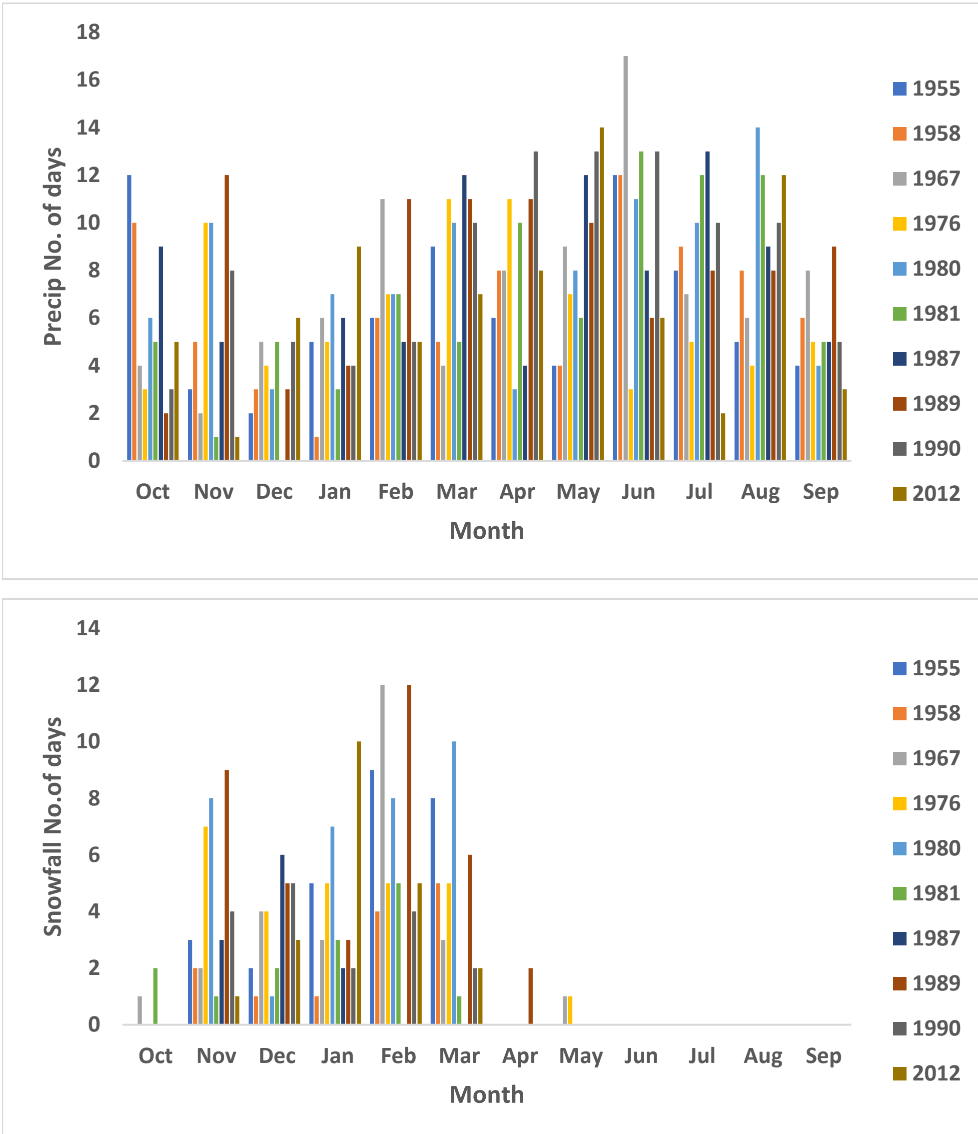


Figure 3.21. Monthly number of days with precipitation and snowfall greater than trace amount for Very Wet climate.

The monthly difference from the average climate in Figure 3.22 shows more precipitation decrease from average monthly precipitation than the increase. The decrease is highest in highest in June 2012 with 3.4 in followed by 3.2 in in June 1976 and 2.9 in in May 1981. The lowest decrease is 0.2 in in most years and months. The highest

increase from the average is in March 1987 with 1.8 in followed by February 2012 with 1.7 in, October 1980 with 1.5 in and April 1967 with 1.4 in, and the lowest increase is 0.1 in in June 1955. There is no increase in December month for Very Dry Climate. This shows that December has less than average precipitation in Very Dry years.

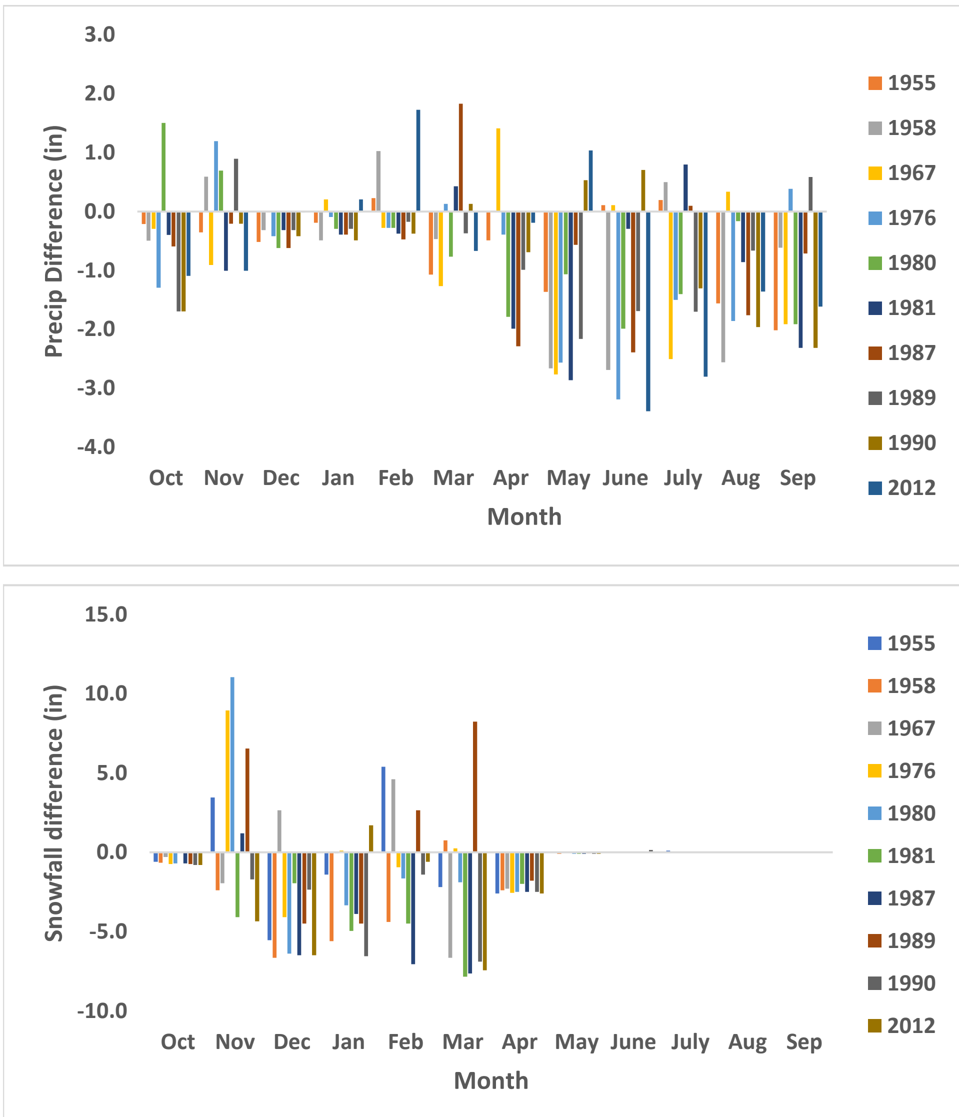


Figure 3.22. Monthly precipitation and snowfall percent difference for Very Dry climate from monthly average climate.

Snowfall monthly difference from the average snowfall shows more decrease than increase. The highest decrease is in March 1981 with 7.9 in. in 1987 with 7.7 in, and 2012 with 7.5 in. The lowest decrease is 0.1 in May for most of the years. The highest increase is November 1980 with 11.1 in, 1976 with 9.0 in , March in 1989 with 8.3 in, and the lowest increase is 0.1 in in May, June and July 1955, and May 1967, and January 1976. There is very low difference in October and May to July.

3.3.3. Comparison of Very Wet and Very Dry climates

3.3.3.1. Annual Variability

The long-term annual average precipitation and snowfall for Sioux Falls are 26 in and 38 in, respectively. The average precipitation (Figure 3.23) and standard deviation for Very Wet are 39 in and 3.4 in and Very Dry are 17 in and 1.4 in and the average snowfall and standard deviation for Very Wet are 62.5 in and 11.9 in and for Very Dry are 25.2 in and 12.2 in.

Precipitation and snowfall for all the years in Very Wet climate are higher than long-term average climate, which is an increase from the average, even though % difference differ with each individual year (Figure 3.3), meaning Very Wet climate receive both high precipitation and snowfall and Very Dry climate has lower precipitation than average climate, and lower snowfall than average except 1989 and 1976 have higher snowfall than average climate (Figure 3.14). The percent difference from average for Very Wet ranged from 33% in 1909 to 70 % in 2010 precipitation while Very Dry ranged from 30 % decrease in 1955 to 48 % decrease in 1976. This shows that the wettest year is 2010 (44 in) and the driest is 1976 (13.5 in) and level of wetness (up to 70%) is higher than the level of dryness (up to 49%). The least very wet year is 1909 and the least very dry year is 1955.

Snowfall total for Very Wet ranged from 52 in 1909 to 82 in 1962 while for Very Dry ranged from 10.3 in. in 1987 to 43.4 in. in 1989. The percent difference from long-term average ranged from 34% 1909 to 116% 1962 for Very Wet and 10% in 1955 to

73% decrease 1987 for Very Dry and there is 1% increase in 1976 . Meaning 1962 had highest snowfall and 1987 had the least snowfall.

The number of days with precipitation ranged from 33% in 1909 to 57 (%) in 2019 and 36% in 2012 to 52 (%) 1967 for Very Wet and Very Dry, respectively. The number of days with snowfall ranged from 10% in 1909 to 24% in 1993 and 11% in 2012 to 22% in 1955. This shows that number of days with precipitation and snowfall do not correspond with precipitation and snowfall totals, the intensity influences the amounts.

Both precipitation and snowfall show increase from average for Very Wet climate while Very Dry show all precipitation decrease, and snowfall show decrease except increase in 1976 and 1989.

Overall, on average, Very Wet climate has high precipitation with 49 % increase while Very Dry climate has low precipitation with 35% decrease. Very Wet climate has high snowfall with 64 % increase from average climate while Very Dry climate has low snowfall with 34 % decrease from average climate (Figure 3.24).

The number of days with precipitation including traces are above average in Very Wet climate indicating that Very Wet climate gets a lot of precipitation days however, the number of days does not correspond with the precipitation or snowfall amounts, the intensity of precipitation or snowfall influences the total. That is, one day could have high amount of precipitation that makes a significant monthly, seasonal, or annual total.

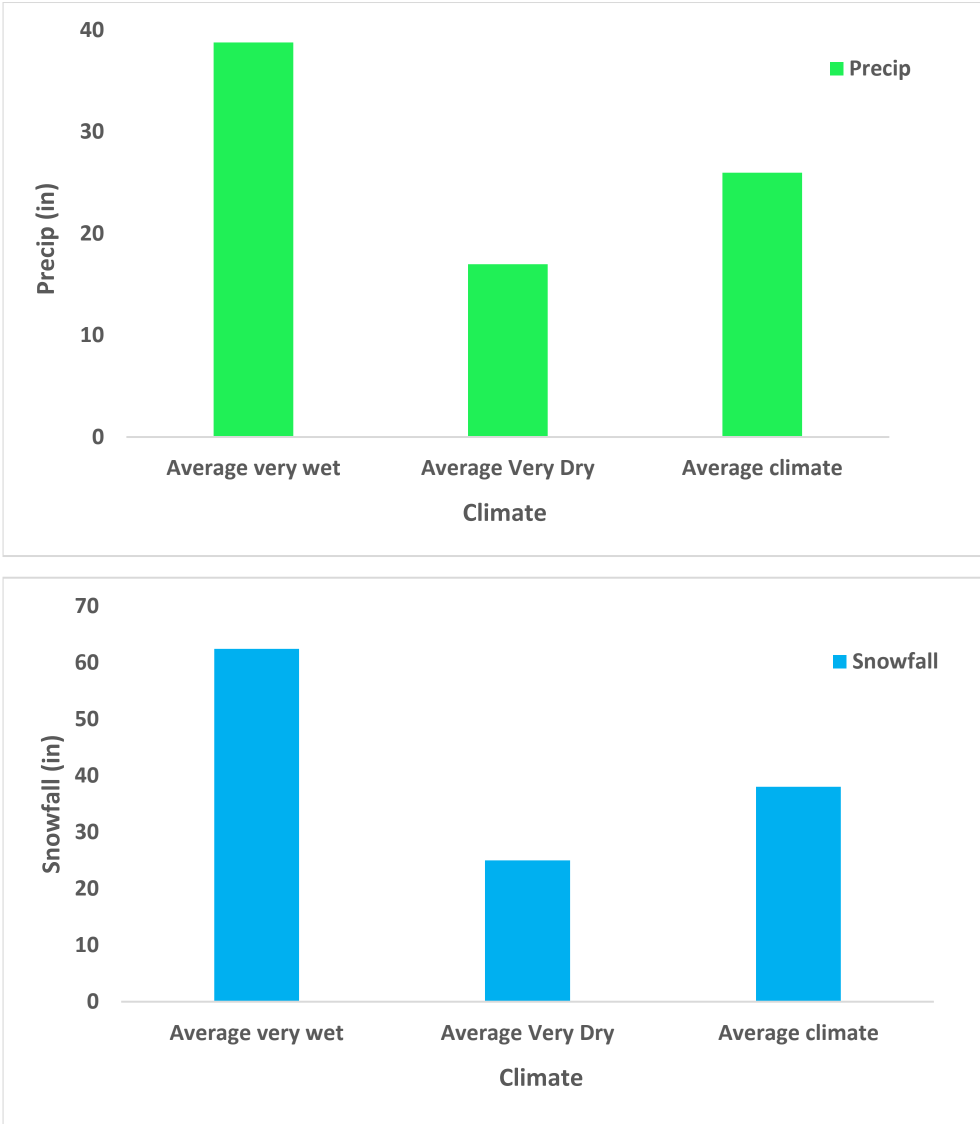


Figure 3.23. Average precipitation and Snowfall for Very Wet and Very Dry climate compared to overall average climate from 1895-2019.

The snowfall days are lower than precipitation days as precipitation is recorded throughout the year and snowfall only from Fall to Spring. The CVs for Very Wet climate are 8.9% and 19% for precipitation and snowfall, respectively, and CVs for Very

Dry are 8.2% and 48.5% for precipitation and snowfall, respectively. This shows that Very Wet climate has a less variable snowfall compared to Very Dry climate.

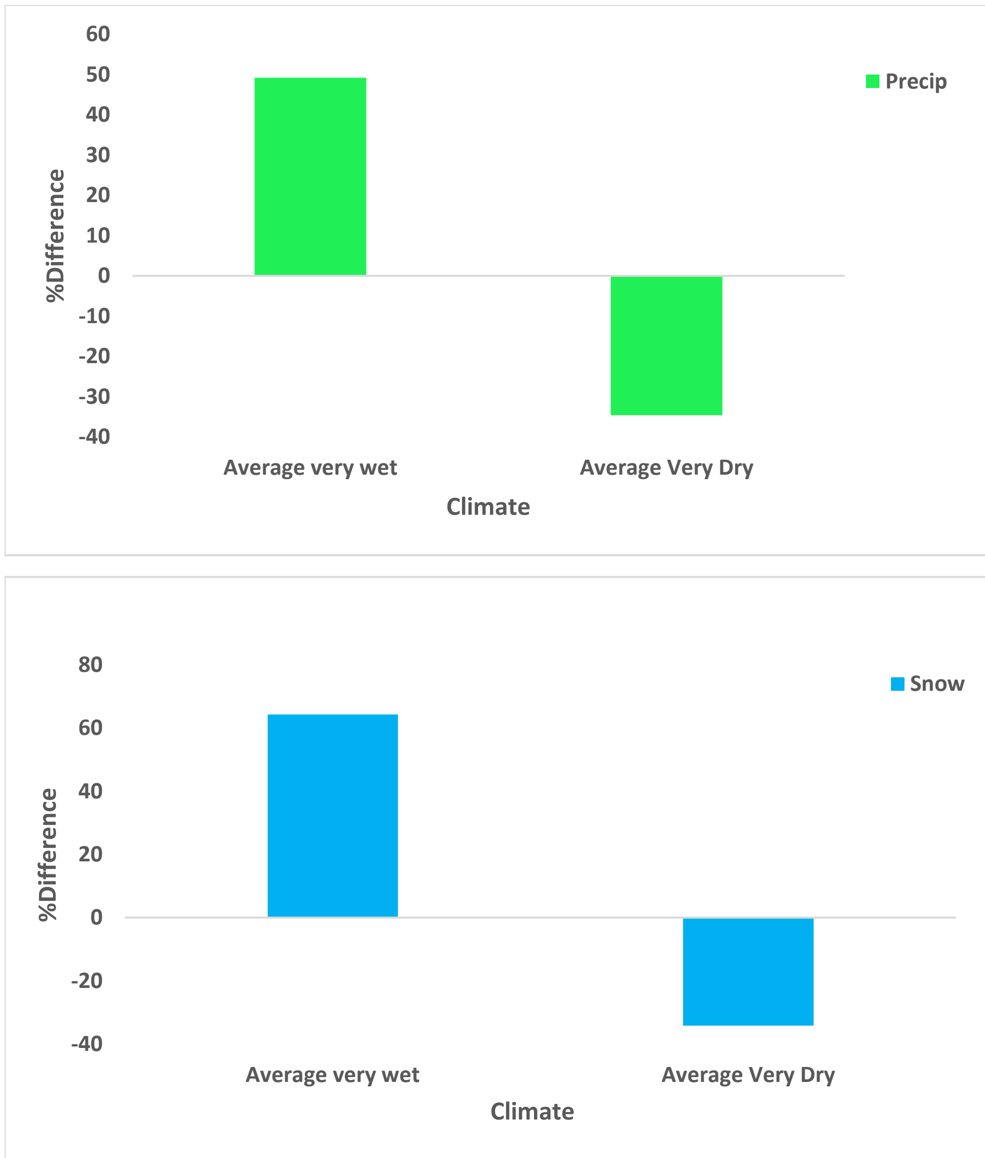


Figure 3.24. The precipitation and snowfall percent difference (%) of Very Wet and Very Dry from the overall annual average climate from 1895-2019.

3.3.3.2. Seasonal variability

Seasonal precipitation for Very Wet climate is higher than long-term average for all the years and snowfall is below average in the Spring as some years do not have snowfall in the Spring. While Very Dry climate show most precipitation is below average even though some years have higher than average, and snowfall is below average in some years and above in some. Precipitation for Very Wet climate ranged from 3.6 in in Winter to 19.4 in in Summer 2010 while Very Dry ranged from 1.4 in. in the Fall in 1990 to 10.8 in. in the Spring in 1990. Snowfall for Very Wet ranged from 0.2 in. in Spring to 45.7 in. in Winter while snowfall for Very Dry ranged from 0.1 in. in the Spring and Summer (1955, 1980, 1987) to 28.8 in. in the Winter in 1989 for snowfall.

Seasonal precipitation difference shows increases for Very Wet and more decrease for Very Dry than increase. Very Wet years have highest increase in Winter with 118.4% 1962 and lowest in Spring 14.5% 1962 for Very Wet. Very Dry has the highest decrease in the Summer 2012 with 65% and lowest in the Winter with 47.1% in 1967.

Snowfall difference for Very Wet is highest in Winter 1962 (45.7 in) and lowest in Spring 1993 (0.2 in) Very Dry has highest in the Winter 1958 with a decrease of 99.1% and lowest decrease is in Winter 1976 with 2.7 %. The highest increase is in the Fall 1980 with 32.2 %, the lowest increase is in the Fall 1967 with 3.2 %.

Number of days with precipitation ranged from 22 in Fall to 65 in Spring for Very Wet and 23 in the Summer in 1976 to 59 in the Spring in 1967 for Very Dry. The number of days with snowfall ranged from 0 in Summer and Spring to 52 (1962) in Winter for

Very Wet and 0 days in the Summer 1955 to 54 days in the Winter 1955 for Very Dry climate. Overall, Winter has a high number of days followed by Fall, Spring, and Summer with low number of days to no days.

On average, seasonal precipitation for Very Wet is higher than average for all seasons while Very Dry is lower than average for all seasons (Figure 3.25). The average seasonal precipitation for Very Wet ranged from 4.6 in. in the Winter to 14.5 in. in the Summer and Very Dry ranged from 2.4 in. in Winter to 6.7 in. in the Spring. The precipitation is highest in the Summer and Spring for Very Wet and Very Dry climates respectively, followed by Fall and lowest in the Winter for both. Very Wet has highest in the Summer while the Very Dry has highest in the Spring indicating that Very Wet climate gets a longer precipitation period and higher amounts rainfall in the Summer while Very Dry gets even lesser precipitation in the Summer. The precipitation in the winter is mainly the melted snow.

Snowfall for Very Wet ranged from 0.1 in. in the Summer to 39.3 in. in the Winter and Very Dry ranged from 0.1 in the Summer to 14.3 in the Winter (Figure 3.25). The snowfall is highest in the Winter, followed by Fall, Spring and Summer with the lowest snowfall for both Very Wet and Very Dry climates. The presence of snowfall in the late Spring and Summer is due to trace precipitation which could be hail.

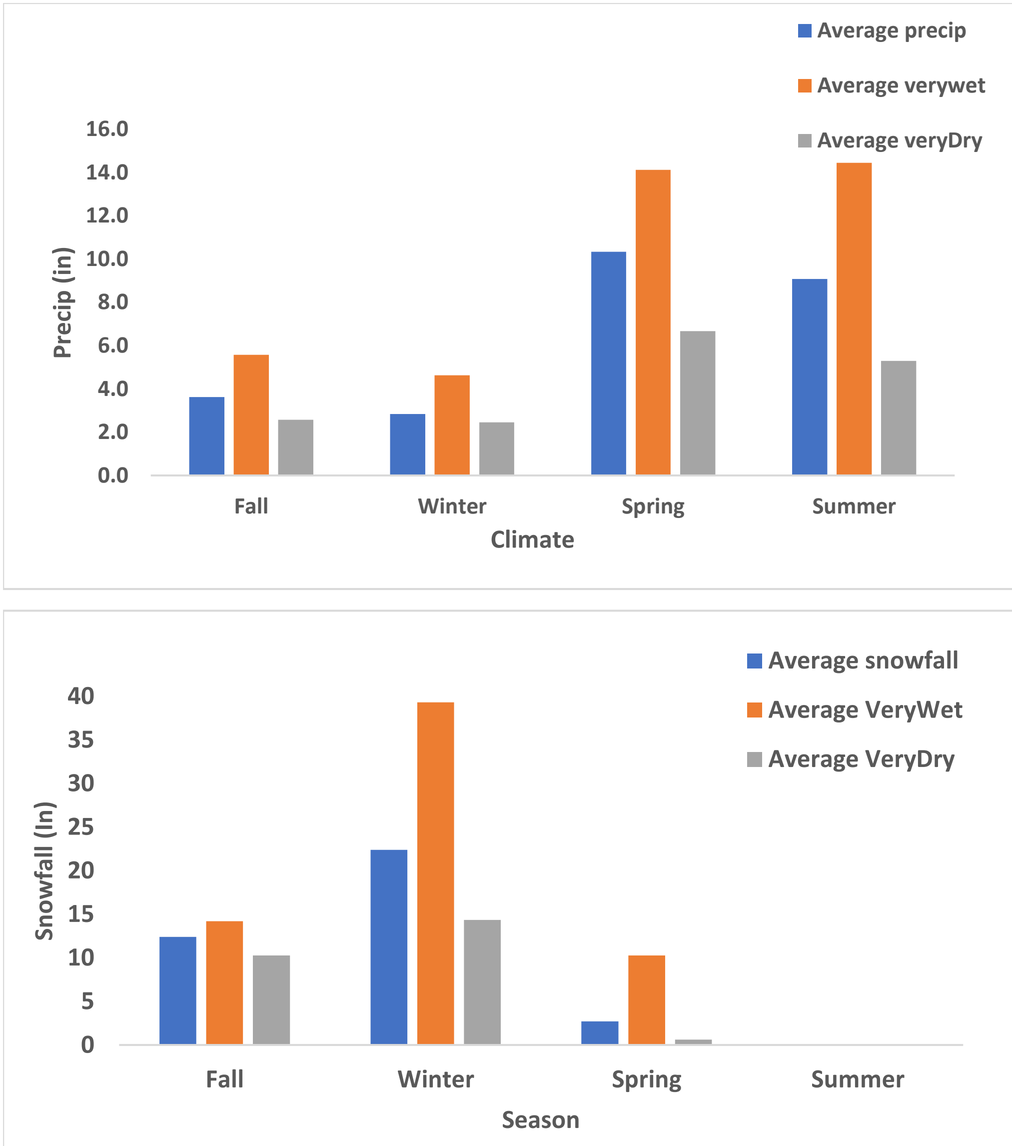


Figure 3.25. Average seasonal precipitation and snowfall for Very Wet and Very Dry climate classifications compared to overall seasonal averages from 1895-2019.

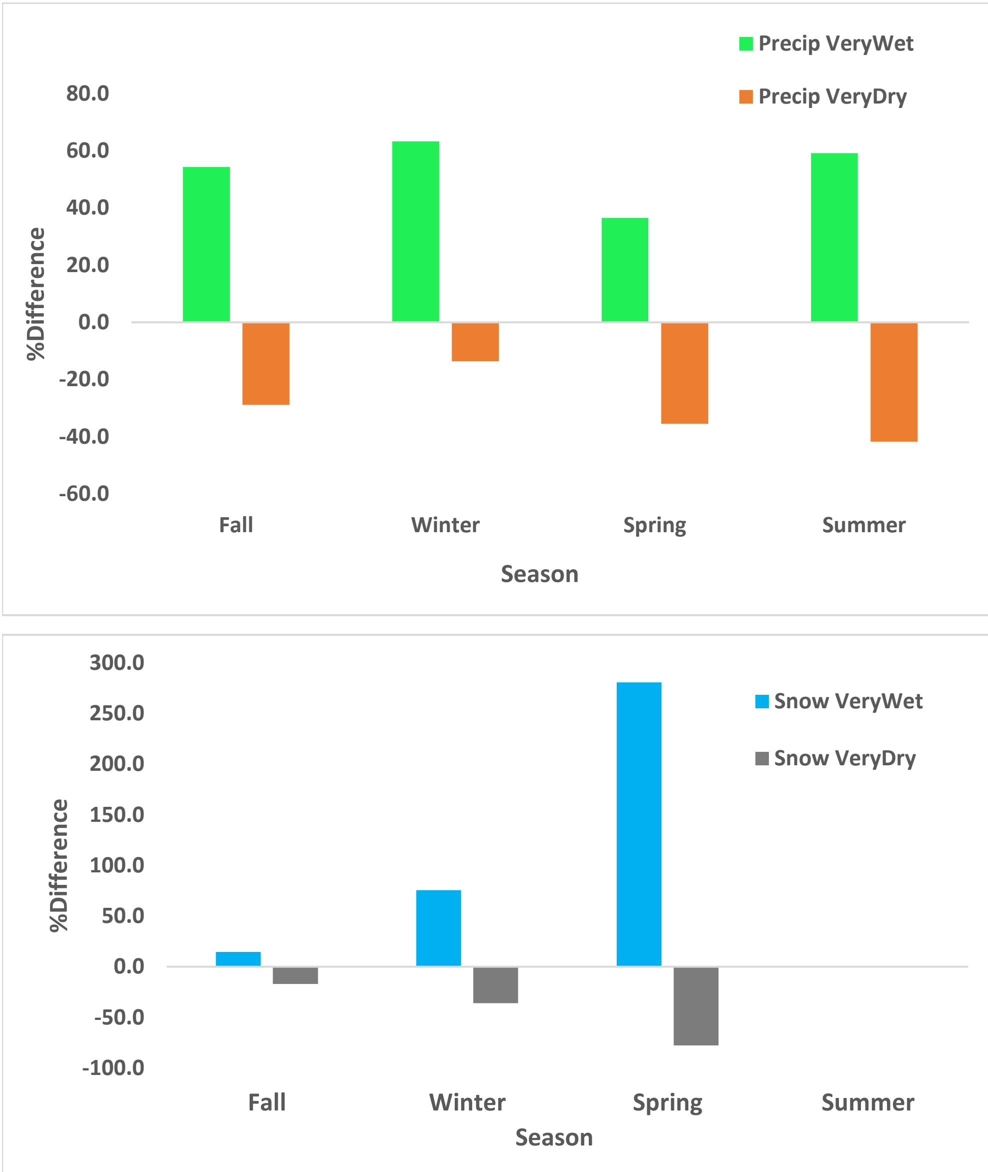


Figure 3.26. Percent differences of average seasonal precipitation and snowfall for Very Wet and Very Dry climate classifications from overall seasonal averages from 1895-2019.

The average seasonal precipitation percent difference from the average climate in Figure 3.26 shows that Very Wet climate is above average with the highest increase in the Winter (63.3%) followed by Summer (59.2%), Fall (54.4%) and lowest in the Spring (36.5%) while Very Dry climate shows a decrease from the average climate for all

seasons (Figure 3.26). The highest decrease is in in the Summer with 41.7% followed by Spring with 35.5%, Fall with 28.8% and lowest in the Winter with 13.6%. The percent difference shows that Very Wet climate highly vary from the average increase compared to Very Dry climate. The seasonal percent difference also vary as Very wet has highest difference in the Winter while Very Dry has highest difference in the Summer.

3.3.3.3. Monthly Variability

Monthly precipitation for Very Wet ranged from 0.1 in. in November 2018 to 8.6 in. in July 2010. November to March have low precipitation while May, June, and July have higher precipitation, even though August and September show higher precipitation in recent years (2018 and 2019). Monthly precipitation for Very Dry ranged from 0.1 in. in October to 4.9 in. in June. Precipitation is lowest in December and January, and highest in June. Generally, May, June, and July have higher precipitation even though April, August, and September show higher amounts in some years. While October, November, December, January, February, and March generally have lower precipitation.

Snowfall for Very Wet ranged from 0.1 to 48.8 in. in February. February shows to have high amounts of snowfall; however, December, January, March, and April also get high snowfall amounts. Very Dry monthly snowfall varies with year, snowfall ranged from 0in in October, and April, to September for most of the years to 16.2 in. in March 1989. November, February, and March shows to have high amounts of snowfall and lowest in May, June, July, August, September.

The number of days with precipitation ranged from 5 days in October 1909 to 25 days in April 2019 for Very Wet. Very Wet has lower monthly number of days

precipitation in March, August, and September, and higher in December, April to June, even though generally every month show to have many days of precipitation. While the number of days with precipitation for Very Dry range from 4 to 24 days.

The difference from the average monthly precipitation shows to have high increase than decrease from the average for Very Wet. July has highest increase in 2010 with 5.5 in and highest precipitation decrease of 1.5 in. in May 2010. December (1909) has the lowest decrease with 0.1 in. Very Dry has more precipitation decrease from average monthly precipitation than the increase. The decrease is highest in June 2012 with 3.4 in and the highest increase from the average is in March 1987 with 1.8 in.

Snowfall difference also shows high increase than decrease from average. The highest increase is in February 1962 with 41.1 in while the highest decrease is in March 2010 with 7.3 in for Very Wet while Very Dry snowfall monthly difference from the average snowfall shows more decrease in many years than increase. The highest decrease is in March 1981 with 7.9 in. The highest increase is November 1980 with 11.1 in,

On average, Very Wet monthly precipitation is higher than average climate ranging from 0.8 in. in January to 6.4 in. in July (Figure 3.27). However, precipitation in November is below average and below very Dry. Very Dry monthly precipitation is lower than average except in February. Precipitation ranged from 0.4 in in January to 4.2 in. in June.

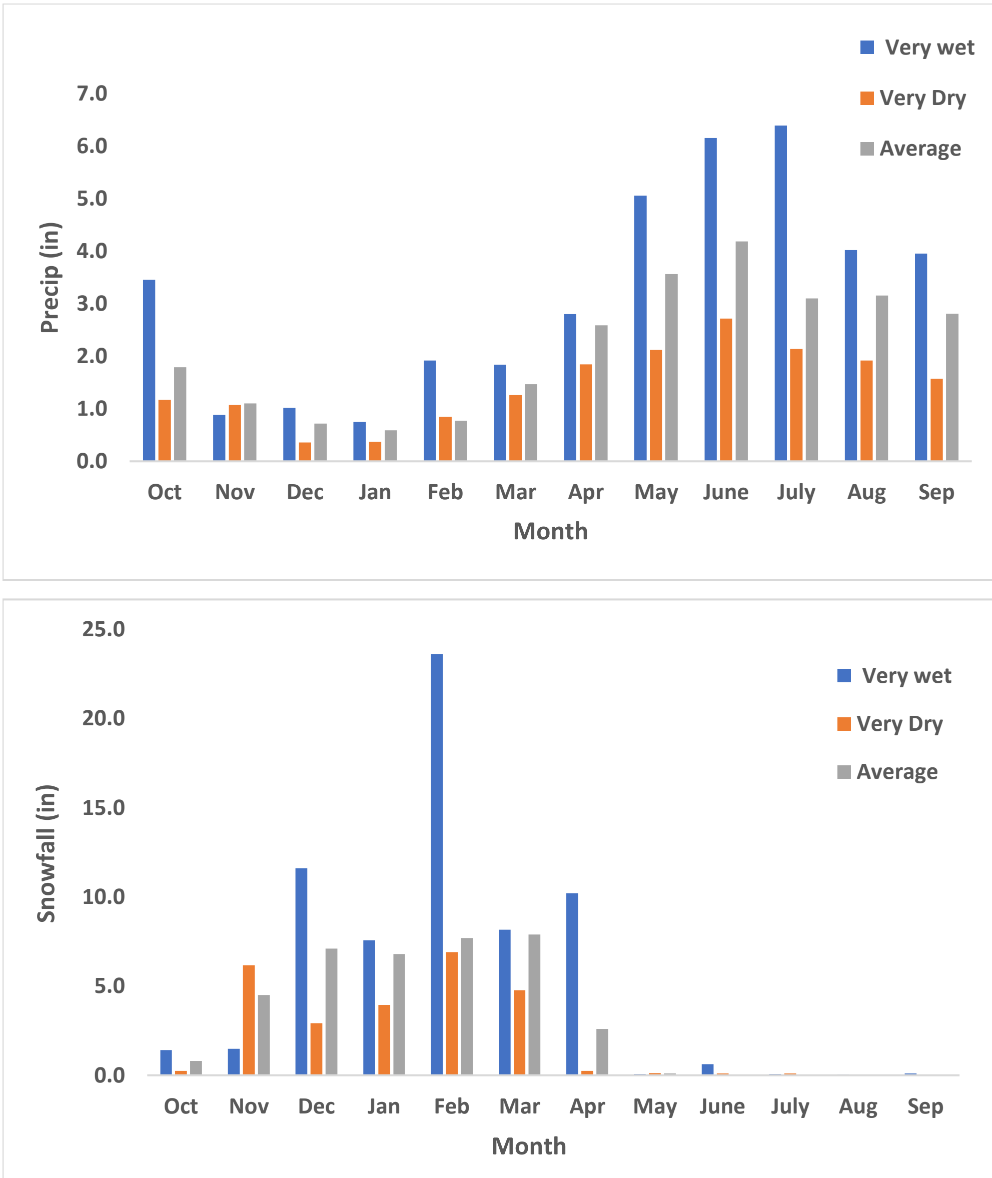


Figure 3.27. Average monthly precipitation and snowfall for Very Wet and Very Dry climate classifications compared to overall monthly averages from 1895-2019.

Snowfall for Very Wet climate is above average except in November where it is below both average and Very Dry (Figure 3.27) while snowfall for very Dry climate is below average except in November. The snowfall for Very Wet ranged from 0 in to 23.6 in. in February while Very Dry ranged from 0 in to 7.9 in. in March. Snowfall is high in

February, April, December, March, and January, for Very Wet while snowfall is high in February, November, March, and January. The presence of snowfall in June for Very Wet is due to solid precipitation such as hail.

The percent difference from average in Figure 3.28 shows that Very Wet has high increase in February with 148% and July with 106% and October with 93 % while lowest increase is in April with 8%. There is a decrease of 20% in November. While very Dry has highest decrease in December with 50% and lowest in November with 3%. There is an increase of 10% in February. The snowfall difference for Very Wet is high increase in April with 293% and February 207% and lowest increase in March with 3%. There is decrease of 67% in November and 33% in May. While Very Dry has high decrease in April with 90% and lowest in decrease in February with 10%.The was an increase of 37% in November and in May with 13%.

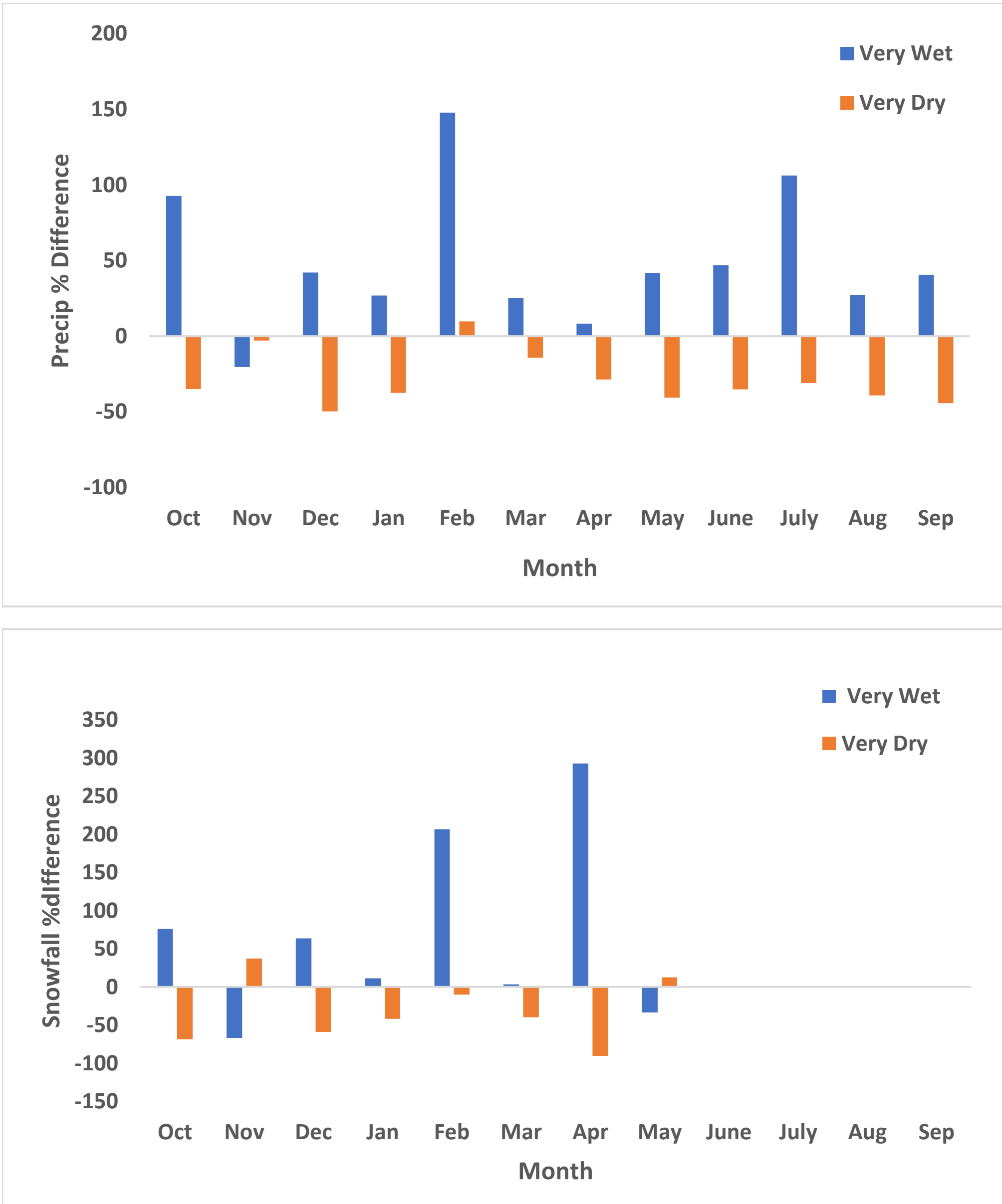


Figure 3.24. Average monthly precipitation and snowfall percent differences for Very Wet and Very Dry climate classifications from overall monthly averages from 1895-2019.

3.4. Discussion Summary

Annual precipitation and snowfall variability for Very Wet and Very Dry climates in Sioux Falls were analyzed for inter and intra variability to quantify their variability and identify any patterns or their absence.

The results show that precipitation and snowfall vary with years, seasons, and months. The wettest year is 2010 (44 in) and the driest year is 1976 (13.5 in). Snowfall is highest in 1962 (82 in) and lowest in 1987 (10.3 in). Very Wet showed an annual precipitation increase of up to 70% (2010) from long-term average and snowfall increase of up to 116% (1962). Very Dry climate showed an annual precipitation decrease of up to 49% (1976) and snowfall decrease of up to 73% (1987). The increase agrees with the study done in the Great Plains that showed 12 to 60% increase in interannual precipitation variability from 1980 to 1999 (Garbrecht & Rossel, 2002). This shows that the level of wetness is higher than that of dryness, meaning the increase in magnitude and intensity of precipitation and snowfall (Powell & Keim, 2015). The increase in precipitation is due to the increase in the intensity of precipitation and the extremely heavy precipitation. This agrees with the studies (Karl & Knight, 1998; Wuebbles et al., 2017) except this study found that the frequency of days with precipitation does not influence the total precipitation. Snowfall has higher interannual variability than precipitation.

Some years have high precipitation and low snowfall, and some have low precipitation but high snowfall, this shows that precipitation and snowfall do not correspond, and high precipitation does not indicate high snowfall. This is because precipitation included the melted snow not the actual snowfall measurement. Analysis of

both precipitation and snowfall is important in areas that receive high snowfall to determine the runoff and flood from snow melt and to determine water availability.

Some years have high precipitation in seasons where some years have low precipitation and the same with snowfall. Some years have high precipitation or snowfall beginning in the Fall while some in the Winter, Spring and Summer. Some have highest precipitation in the Spring while some have highest in the Summer. This indicates a highly variable climate and less predictable climate, and this creates a challenge for water planners and engineers about the availability of water, early preparation and forecasting of extreme climate, floods, and droughts. Seasonal precipitation and snowfall vary with years, but generally, Summer has highest precipitation followed by Spring, Fall and Winter for Very Wet while Very Dry has highest precipitation in Spring followed by Summer, Fall and Winter. Winter has highest snowfall followed by Fall, Spring, and Summer with less or no snowfall for both Very Wet and Very Dry climates. The Wettest year 2010 showed to have higher precipitation from Fall to July and snowfall from Fall to April. This shows that Very Wet climate has higher precipitation in all seasons compared to Very Dry. Snowfall also differs from Fall to Spring and is highest in the Winter even though 2018 has high snowfall in the Spring .

On average, Both Very Wet and Very Dry have lowest precipitation in January while they have highest in July and June, respectively. Very Dry had higher precipitation and snowfall in November than Very Wet and long-term average. This shows that, in November, Very Dry climate received higher precipitation.

The presence of snowfall in the Summer and late Spring is due to traces from solid precipitation such as hail. The traces amounts are high in months that usually do not

get snowfall or get very less snowfall and months and seasons that get less precipitation or no precipitation. Traces could be excluded depending on the users' goals. Precipitation and snowfall in Very Wet climate show increase from average climate and Very Dry climates show decrease from average climate. The level of increase in precipitation and snowfall is higher than the level of decrease meaning climate is getting more wet than dry indicating high potential of floods than drought.

3.4. Summary and Conclusions

Annual precipitation and snowfall variability for Very Wet and Very Dry climates from 1895 to 2019 were analyzed for Sioux Falls to quantify inter and intra variability and identify any patterns or their absence. The following conclusions are made:

- Precipitation and snowfall vary with years. The wettest year is 2010 (44 in) and the driest year is 1976 (13.5 in). Very Wet climate has higher precipitation from long-term average with up to 70% increase while Very Dry climate has lower precipitation from long-term average with up to 49% decrease. Snowfall is highest in 1962 (82 in) and lowest in 1987 (10.3 in) from the average. Snowfall has high interannual variability than precipitation. The level of increase in precipitation and snowfall is higher than the level of decrease meaning climate is getting more wet than dry for this study period. This is due to the increase in precipitation magnitude.
- Seasonal precipitation varies with years and with each climate classification. Very Wet show highest increase from average in Winter (118.4% in 1962) and lowest in Spring (14.5.% in 1962) while Very Dry has the highest decrease in the Summer (65% in 2012) and lowest in Winter (47.1% in 1967). Snowfall

difference for Very Wet is highest in Winter 1962 (45.7 in) and lowest in Spring 1993 (0.2 in) Very Dry has highest in the Winter 1958 with a decrease of 99.1% and lowest decrease is in Winter 1976 with 2.7%. The highest increase is in the Fall 1980 with 32.2%, the lowest increase is in the Fall 1967 with 3.2%. Seasonal precipitation and snowfall vary with years, but generally, Summer has highest precipitation followed by Spring, Fall and Winter for Very Wet while Very Dry has highest precipitation in Spring followed by Summer, Fall and Winter. Winter has highest snowfall followed by Fall, Spring, and Summer with less or no snowfall for both Very Wet and Very Dry climates. Overall, Spring has highest number of precipitation days, followed by Winter and Summer and Fall with lowest and number of days with snowfall is highest in Winter followed by Fall, Spring, and Summer.

- Generally, May, June, and July have higher precipitation even though April, August, and September show higher amounts in some years. While October, November, December, January, February, and March generally have lower precipitation. Both precipitation and snowfall show high increase than decrease from the average from the average monthly precipitation for Very Wet and there is higher decrease than increase for Very dry climate. On average, Both Very Wet and very Dry have lowest precipitation in January while they have highest in July and June, respectively. Very Dry has higher precipitation in November than Very Wet and long-term climate average.

- Precipitation does not correspond with snowfall as some years have high precipitation and low snowfall and some have high snowfall and low precipitation.
- The number of days is above average, but do not correspond with precipitation or snowfall amounts as some days have little or trace precipitation which increases the number of days with precipitation but do not increase the amount of precipitation. Precipitation intensity influences the amounts. The presence of snowfall in the late Spring and Summer months is due to traces from solid precipitation such as hail and frost.

The findings provided can be incorporated in planning and management of water resources including updating precipitation for infrastructure designs at the local scale as opposed to IDF curves that use regional data that could result in underestimation or overestimation in designs. The findings provide support for further investigations for water and climate research.

Chapter 4: Long-Term Streamflow and Precipitation Correlation, Peak Flows and Floods Events.

Abstract

Floods are the leading climate and weather disasters that continue to have severe impacts on the society and the economy. In addition to precipitation variability and extremes, land use changes due to urbanization, that increase imperviousness, exaggerate the flooding. In areas that receive high amounts of snow, early spring snowmelt also causes flooding. The in-depth knowledge of precipitation and streamflow relationship at a local scale can aid in understanding of floods and droughts and aid in water resources management, flood forecasting and mitigations. This study used statistical methods to analyze precipitation and streamflow correlation, peakflows, and flood events. The results show no daily correlation (0.1- 0.18). Spring show moderate correlation (0.54) followed by summer (0.48). Winter shows a weak correlation (0.38) and Fall show very poor correlation (0.25). Annual correlation is higher than of seasonal and stream gauges show moderate to weak correlation (0.57- 0.49) The stream gauges in the same drainage area with precipitation gauge have higher correlation. Flood events were identified in each gauge and the Big Sioux River at Sioux Falls had 27 flood events which are minor, moderate, and major, the Big Sioux River at North Cliff Avenue, which is the outlet of the watershed had 20 flood events which are minor and moderate, the Skunk Creek also had minor, moderate and major floods with total of 13 floods, and there were no flood events at Big Sioux River Below Diversion, demonstrating the effectiveness of flood reduction at the airport. Floods events in March to May could be mainly due to snowmelt and in the Summer months (June to September) are due to liquid precipitation. The areas

around the gauges with flood events are in major risk of flood damages indicating the need to reduce the risks.

4.1. Introduction

Climate variability is an important concern globally due to increase in intense and frequent climate and weather. Whether naturally occurring or due to anthropogenic changes in the atmospheric concentration of greenhouse gases (GHGs), especially carbon dioxide, which have caused changes in climate system (IPCC, 2007), climate has become more variable and intense. The increase in frequent and severe climate such as heavy precipitation, snowstorms, floods, droughts, heatwaves, and other extremes have caused significant losses and damages to civilization (Floodlist, 2019; NOAA, 2020; UN, 2002; UNDRR, 2002). This creates a concern in the infrastructure designs and floods mitigations, that are based on stationary precipitation assumption, meaning precipitation would not significantly change over time. The literature states that stationarity concept even though still used is no longer valid (Khaliq et al., 2006; Milly et al., 2008; Tramblay et al., 2013; Westra & Sisson, 2011), therefore there is a need to evaluate and update the Intensity-duration-frequency (IDF) curves used for designs of storm infrastructure.

In addition to climate variability and change, population growth, industrialization, urbanization results in land use changes that consequently alter the hydrologic system (Cristiano et al., 2017). These kind of changes result in high imperviousness that cause increase in runoff, high peak flows, early time to peak, and water quality issues (Bates et al., 2008). These amplifies the risk of flooding as runoff in small watersheds is sensitive to small-scale spatial and temporal precipitation variability and land use (Biemans et al., 2009; Cristiano et al., 2017; DeWalle et al., 2000). Therefore, evaluating climate

variability in terms of long-term heavy or extreme precipitation and how it relates to long-term streamflow and peak flows is important to quantify non stationarity and evaluate floods.

It is critical to evaluate precipitation and streamflow variability to have an in-depth understanding of how they relate and quantify variability as precipitation influences flows. This would in turn aid in making necessary adjustments and predictions which are based on historical records, needed to be made earlier than the extreme happens. Precipitation and streamflow aid in water resources management related to drought, floods, and reservoir operations. Precipitation runoff in a watershed influences streamflow by causing the rivers to rise, even if precipitation is far up in the watershed, it eventually drains to the outlet.

Hourly precipitation and daily streamflow in Ireland were used to investigate patterns of climate variability and found increase in annual precipitation after 1975 and in March and October and same trends in streamflow. Extreme precipitation events mainly occurred from 1975 (Kiely, 1999). Precipitation, streamflow, and evapotranspiration trends in the Great Plains showed that upward trend in precipitation had a strong impact on streamflow and weaker impact on evapotranspiration and increased precipitation led to a disproportionately large increase in streamflow and smaller increase in evapotranspiration (Garbrecht et al., 2004). The study done in 5 states in USA shows that using current Intensity-Duration-Frequency (IDF) curves, which assume stationary precipitation, extreme precipitation may be underestimated by 60 % under non-stationary (Cheng & AghaKouchak, 2014). The study in Maryland showed an increase of 30% in

100-year flood in non-stationary flood frequency analysis method that account for urbanization and climate change for 2100 design year (Gilroy & McCuen, 2012).

The literature is documented on global and regional scales but the quantification at local scale is necessary for local planning and management. This study aims to fill this gap by analyzing precipitation and streamflow at local scale. The purpose of this study is to quantify how long-term precipitation events relate to long-term flow events and analyze flood events to quantify climate variability under non-stationary precipitation.

4.1.1. Specific Objectives are to:

1. Quantify daily, seasonal, and annual correlation between streamflow and precipitation.
2. Assess peak flow events, flood events, and climate variability impacts.

4.2. Methodology

4.2.1. Geography of Study Area

The study was done in Sioux Falls, the biggest city in South Dakota, United States of America. Sioux Falls is in Minnehaha County and extends into Lincoln County (Figure 4.1). Sioux Falls is in the Big Sioux River Valley in southeastern South Dakota, United States (Figure 4.2). It is located at 43.55ºN, 96.73ºW and lies 1421 feet above sea level. Big Sioux River is the biggest tributary that flows through Sioux Falls. There is Diversion Canal along Big Sioux River to reduce flooding at the airport during snow melt. According to U.S. Census Bureau (USCB, 2018) Sioux Falls covers about 78.04 square miles of which 77.5 square miles is land and 0.53 square miles is water. The population is about 183,793 as of 2019 census. The land uses are residential and

commercial areas, pastures, croplands, hayfields, forests, and farmlands (Chuang et al., 2011). The dominant soil groups are C and D (USDA, 2021). The annual average temperature is 45.1 Fahrenheit (^{o}F) and averages with 14 ^{o}F in January, and 73 ^{o}F in July. The average annual precipitation is 25 inches of rain and 38.1 inches in snow.

Sioux Falls has a continental climate with four seasons, Fall, Winter, Spring, and Summer. The seasons range from warm or hot and humid Summers to cold and dry Winters (Atlas, 2020). July is the hottest month with many days with 90 ^{o}F to 100+ ^{o}F. Sioux Falls is susceptible to thunderstorms and tornadoes in late Spring and early Summers. January is coldest in Winter with temperatures below freezing with snowfall up to 8in. February is a chilly month with very cold nights and blizzards are common during this time. March gets frequent snowstorms, and it is the start of Spring season.

The location of the precipitation weather stations used in this study is at Sioux Falls Foss Field in-between the Big Sioux River and the Diversion Canal and streamflow gauges are in the Big Sioux River around the airport (Figure 4.2). The gauges information is in Table 4.1. All gauges are in Hydrologic Unit 10170203, Minnehaha County in South Dakota.

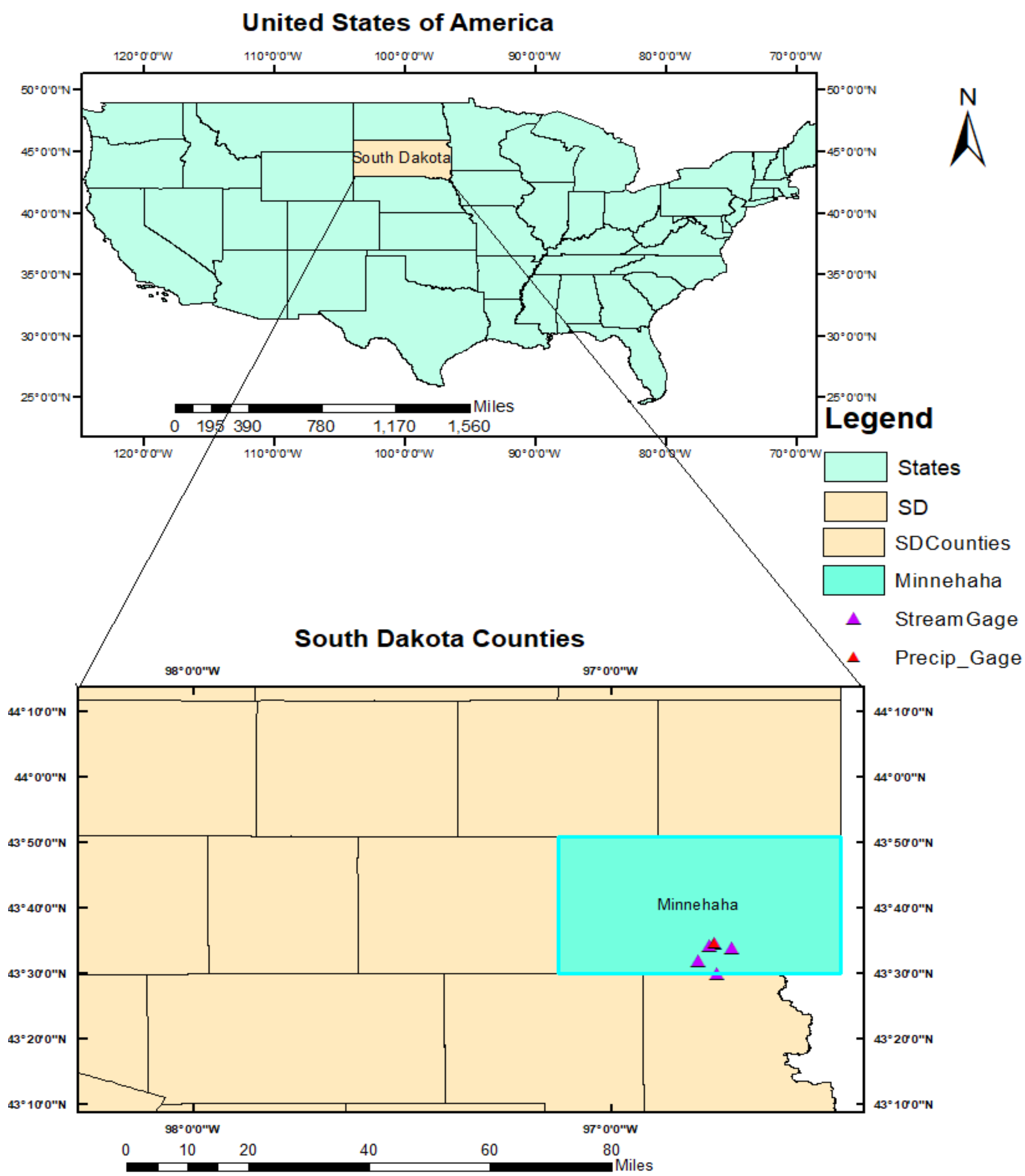


Figure 4.1. Location of Gauges in Minnehaha County in South Dakota.

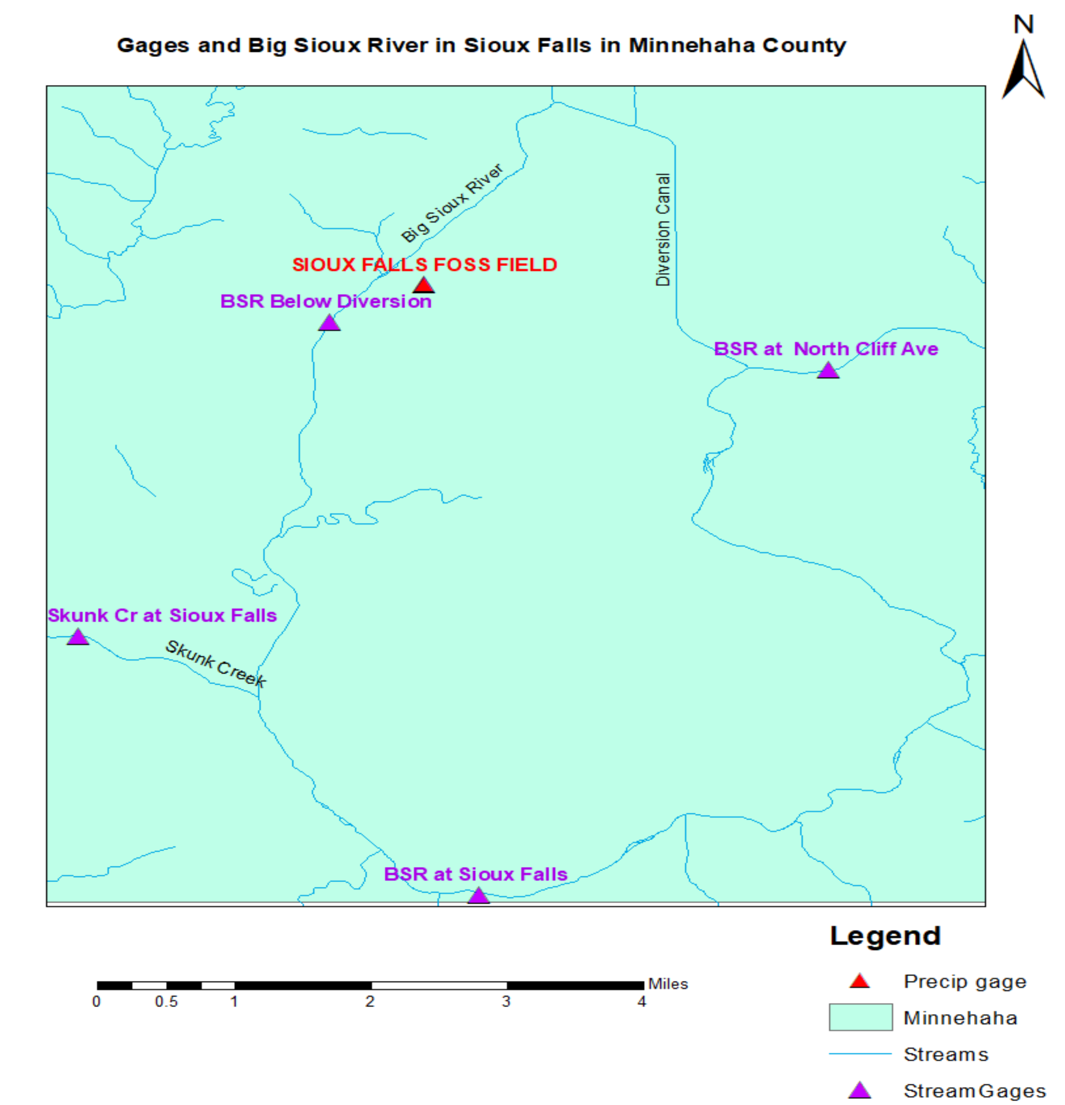


Figure 4.2. Location of weather stations in the Big Sioux River in Sioux Falls, Minnehaha County.

4.2.2. Description of the Study Area

Sioux Falls is the largest, most populous city in South Dakota, United States of America and it is a rapid growing city that has grown over the years. The increase in development and rapid urbanization in recent years has greatly increased impervious land cover, causing increase in surface runoff, high peak flows rates and time to peak. Flooding has become frequent hazard due to extreme precipitation events and late spring snowmelt and resulting in destruction of properties and water quality issues (Argus Leader, 2019a; Dakota News Now, 2019; NWS Sioux Falls, 2019). Sioux Falls experiences both flash floods due to high imperviousness during heavy rain, areal floods due to heavy rains and snow melt, and river floods due to heavy rain and or snow melt that increase water levels and river/stream overflow (Argus Leader, 2019a, 2019b; NWS Sioux Falls, 2019). Recent years flooding has impacted people and destroyed properties (Court Listener, 2017; Dakota News Now, 2019)The drainage systems are usually designed to drain minor storms of 5-year return period to provide protection against damages recurring regularly, and major storms of 100-year return period which should prevent major property damage and loss of life (City of Sioux Falls, 2021), however, heavier storms' runoff may exceed the existing drainage capacity, thus causing flooding. Therefore, the design storms for drainage infrastructure needs to be evaluated to see if they are accommodative of the magnitude of floods experienced in this area.

4.2.3. Data

Daily listing precipitation data from Sioux Falls Foss Field, FSO 397667 (Coop) was extracted from High Plains Regional Climate Center (CLIMOD, 2020). The daily listing is the daily sum. Daily discharge data (mean), peak flow and gauge height from

the stream gauges was extracted from USGS water data (USGS, 2021). The discharge data is the streamflow data. The period of record in these stations vary and some stations have years of missing data, therefore, only years with consistent data were used in some stations. Table 4.1 shows the summary of the information about weather stations. The USGS provides Streamflow data labeled as A:Approved for publication -- Processing and review completed, P: Provisional data subject to revision, and e: Value has been estimated. In this study, data used was labeled as A-approved for publication and processing and review completed and A-e meaning value is estimated and approved for publication. Consistent period of record is necessary in characterizing weather and climate extremes; however, data availability causes limitations. Streamflow records are shorter due to the later gauge recordings for data at these locations which are from later 1900s. Therefore, precipitation records were shortened to match streamflow data records.

4.2.3.1. Quality control

Quality control was performed to assess the quality of data and estimate missing data. In this study, precipitation had traces but no missing data, quality control was performed to estimate in traces. Traces are precipitation less than 0.01 in. The user decides on how to treat traces (Yang et al., 1999), therefore, 0.005 in. was used to estimate traces. Streamflow data had gaps in other stations and no estimation was performed. Only the portion of period of record with continuous data were used. The peak flow and gauge height data did not have gaps.

Table 4.1. Streamflow gauges and precipitation stations information in Big Sioux River, Sioux Falls.

Streamflow gauges in Sioux Falls										
									Period of record	
Station Id (USGS)	Station Name	County	Hydrologic unit	Latitude	Longitude	Drainage area (mi^2)	Contributing Area (mi^2)	Datum of gauge (ft)	Stream flow	Peak flow
6482020	BSR at North Cliff	Minnehaha	10170203	43.56703	-96.711	4,662	3,778	1,295.08	1971-2021	1969-2020
6481400	BSR Below Diversion	Minnehaha	10170203	43.57306	-96.7639	3,999	3,129	1,404.48	No data	2003-2021
6482000	BSR at Sioux Falls	Minnehaha	10170203	43.50111	-96.74806	4,642	3,759	1,393.73	1943-2021	1944-2020
6481500	Skunk CR	Minnehaha	10170203	43.53361	-96.79056	620	606	1,401.02	1948-2021	1949-2020

Precipitation station

ID (COOP)	Name	County	Hydrologic unit	Climate division	Elevation	Latitude	Longitude	period of record
397667	Sioux Falls Foss Field	Minnehaha	10170203	South East	1428	43.5778	-96.7539	1893-2021

Table 4.2. The distance of stream gauge stations at Big Sioux River from precipitation gauge.

Station ID	Station name	Distance (mile)
397667 (coop)	Sioux Falls Foss Field	Precipitation Station
USGS 6482020	BSR at North Cliff	2
USGS 6481400	BSR Below Diversion	0.6
USGS 6482000	BSR at Sioux Falls	5.2
USGS 6481500	Skunk CR	3.5

4.2.4. Data analysis

The correlation between streamflow and precipitation was assessed for all stations. First the correlation between daily average streamflow and daily total precipitation for each water year was analyzed for Big Sioux River at North Cliff Avenue gauge. Big Sioux River at North Cliff Avenue gauge is the main gauge in this study as it is the outlet of the watershed. Water year is a 12-month period that starts from October 1st of any given year to September 30th of the following year. The year that has many months (9 out of 12) is the water year, that is, 2019 water year is from October 1st, 2018, to September 30th, 2019 (USGS, 2019),

Daily average streamflow and daily total precipitation were aggregated into monthly streamflow and precipitation and monthly data was aggregated into seasonal data using criteria in Table 4.3. Then seasonal correlation between streamflow and precipitation for Big Sioux River at North Cliff Avenue gauge was performed. The

monthly streamflow and precipitation were aggregated into annual streamflow for each water year. Then annual correlation was performed for Big Sioux River at North Cliff Avenue gauge.

Table 4.3. Months in each season according to water year (USGS, 2019)

Seasons	**Months**
Fall	October-November-December
Winter	January-February-March
Spring	April-May-June
Summer	July-August-September

After the correlation at Big Sioux River at North Cliff Avenue gauge was performed, the daily and annual correlation from other stream gauges at the Big Sioux River were assessed following the same procedure as above to investigate which stream gauge has a better correlation with the precipitation gauge as it is the only gauge used for precipitation. The gauge correlations were analyzed and compared with Big Sioux River at North Cliff Avenue gauge which is the outlet of the watershed.

The peak flow and gauge height were plotted against each and used to identify flood events and their corresponding flows. Figure 4.3 shows the stage flow diagram for Big Sioux River at North Cliff Avenue gauge. At gauge height 14ft it is the action stage, at gauge height 16ft it is the minor flood, at gauge height 18ft is moderate flood, and at gauge height 31ft is major flood. The flood stage is at 16ft. The peak flow events in each stage category were assessed to see climate classification they fall into and the precipitation leading to peak flow in each was assessed. The similar stage flow diagrams

for other gauges were used to assess stage categories and floods events for other stream gauges using the same method and Table 4.4 shows the stream gauges' height range for each stage category.

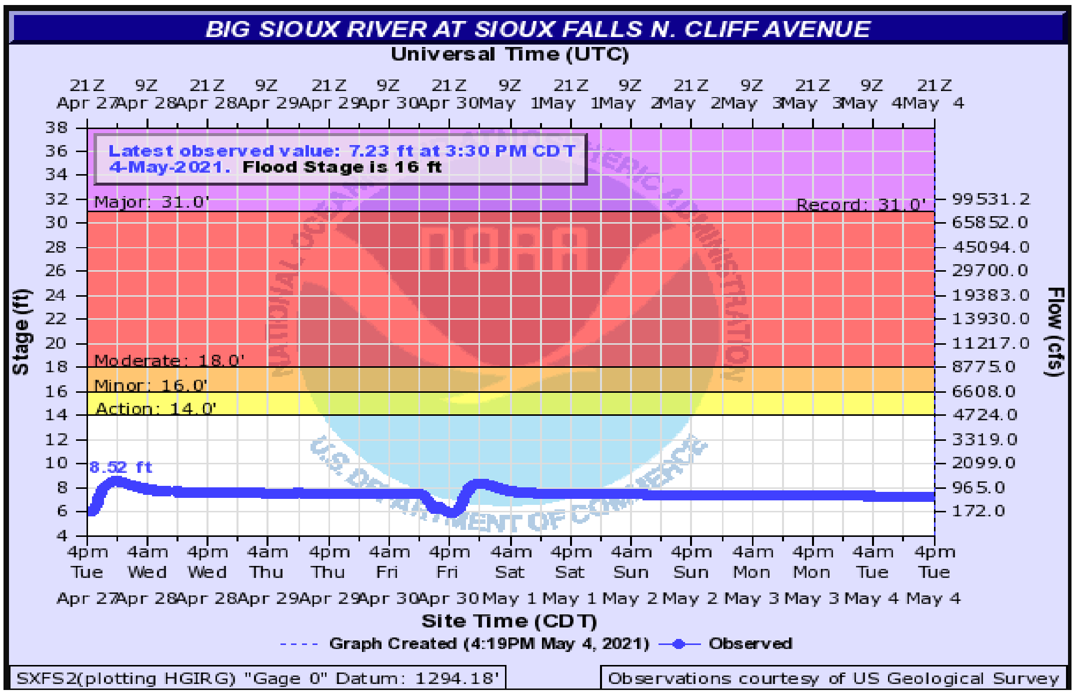


Figure 4.3. Stage flow diagram and the lines showing stage categories and flood stage for Big Sioux River N Cliff Avenue gauge (USGS, 2021).

Table 4.4. Gauge heights for each stage category for each stream gauge in the Big Sioux River in Sioux Falls, identified from stage flow diagram for each gauge (USGS 2021).

Gauge height for each stage categories for each gauge				
Gauge	Action	Flood stages	Moderate stage	Major stage
BSR at North Cliff	14	16	18	31
BSR Below diversion	14	15	18	21
BSR at Sioux Falls	7	8	12	14
Skunk Cr	9.5	11.5	15	17

4.2.5. Statistical Methods

The following statistical procedure was used to analyze precipitation data.

4.2.4.1. Skewness

Skewness is a measure of the degree of asymmetry of a distribution. A normal distribution is symmetric about the mean with a bell-shaped frequency curve (Yamane, 1973). A distribution is skewed if the tail on one side of the distribution is longer than the tail on the other side. If the data is skewed in the direction of higher values, it is positive skewed, if it is skewed in lower values, it has a negative skewness. In a perfect distribution called symmetric, there is no skewness and the skew value will be zero (Freund et al., 1927). If the skewness is less than -1 or greater than 1, the distribution is highly skewed. If skewness is between -1 and -0. 5 or between 0.5 and 1, the distribution is moderately skewed. If skewness is between -0.5 and 0.5, the distribution is approximately symmetrical (GoodData, 2019). The equation for skew function in excel is (Microsoft, 2021):

$$\frac{n}{(n-1)(n-2)}\sum\left(\frac{x_i-\mu}{\sigma}\right)^3 \tag{1}$$

Where n is number of values, μ is mean, x is observed value.

2.2.4.2. Average (mean)

Average (mean) is the sum of all observed values divided by number of values (Freund et al., 1927). It is commonly referred to as average. It is defined by:

$$\mu = \frac{1}{\mathrm{n}} \sum_{i=1}^{n} x_i \qquad (2)$$

Where μ is mean, n is number of values, x is observed value.

2.2.4.3. Standard deviation

The standard deviation (σ) of a data set is the positive square root of its variance (Freund et al., 1927; Yamane, 1973). The variance of a data set is the measure of how much values in a dataset differ from their mean. It is the squared difference from the mean. The standard deviation is the calculation of how much a data set deviates from its mean. A low standard deviation indicates values tend to be closer to the mean (expected value) of the data set while high standard deviation indicates values are spread out over a wide range. It is defined by:

$$\sigma = \sqrt{\frac{\sum (x_i - \mu)^2}{n}} \qquad (3)$$

Where σ is standard deviation, μ is mean, n is number of values, x is observed value.

1.2.4.4. Correlation Coefficient

Determines the relationship between two variables. It demonstrates a linear relationship between each other. Correlation coefficient is between +1 or -1 and correlation coefficient closer to 0 indicates no or weak correlation. Positive correlation means if the value in one variable increases, the value in another variable increases, negative correlation means if the value in one variable increases, the value in another sample is decreasing. Zero correlation means for every increase, there is no positive or negative increase. Two are not related. It is defined by:

$$Correl(X,Y) = \frac{\sum(x-\mu)(y-\mu)}{\sqrt{\sum(x-\mu)^2 \sum(y-\mu)^2}}$$

Where x and y are variables and μ is average of x and average of y.

4.3. Results and Discussion

4.3.1. Precipitation and Streamflow Correlation

Daily streamflow and precipitation for Big Sioux River at North Cliff Avenue from 1972-2019 water year ranged from 0.81 cfs (1982) to 24,300 cfs (2019) and 0 in to 4.59 in (1975) respectively, with the averages of 816.2 cfs for streamflow to 0.07 in precipitation (Figure 4.4). This indicates that 1982 has the lowest streamflow. The daily streamflow and precipitation show very poor correlation of 0.10 with R square of 0.01 meaning no rainfall runoff relationship on a daily basis. This is because the streamflow is a result precipitation upstream and runoff that happens after infiltration capacity is reached and when the soil is saturated, meaning the precipitation of prior days contributes to the streamflow therefore the same day precipitation when streamflow is measured cannot only represent the streamflow. This could also be due to the distant location of the precipitation gauge (2 miles) used as the precipitation gauge at the streamflow gauge location lacked data.

Figure 4.5 shows the seasonal correlation and Spring has highest correlation with 0.54 with followed by Summer with 0.48, Winter with 0.38, and Fall with 0.25, meaning Spring and Summer have stronger correlation indicating rainfall runoff relationship for streamflow and Winter has weak correlation and Fall has the weakest correlation

indicating very low rainfall runoff relationship. The snowmelt in the Spring due to Winter precipitation increase the ground water levels and increase streamflow and rainfall in the spring and Summer contribute to streamflow. Fall has less precipitation and precipitation start to Fall as snow and Winter has frozen ground due to low temperatures, however, the last month of Winter, March, temperatures start to increase thus increasing the snowmelt.

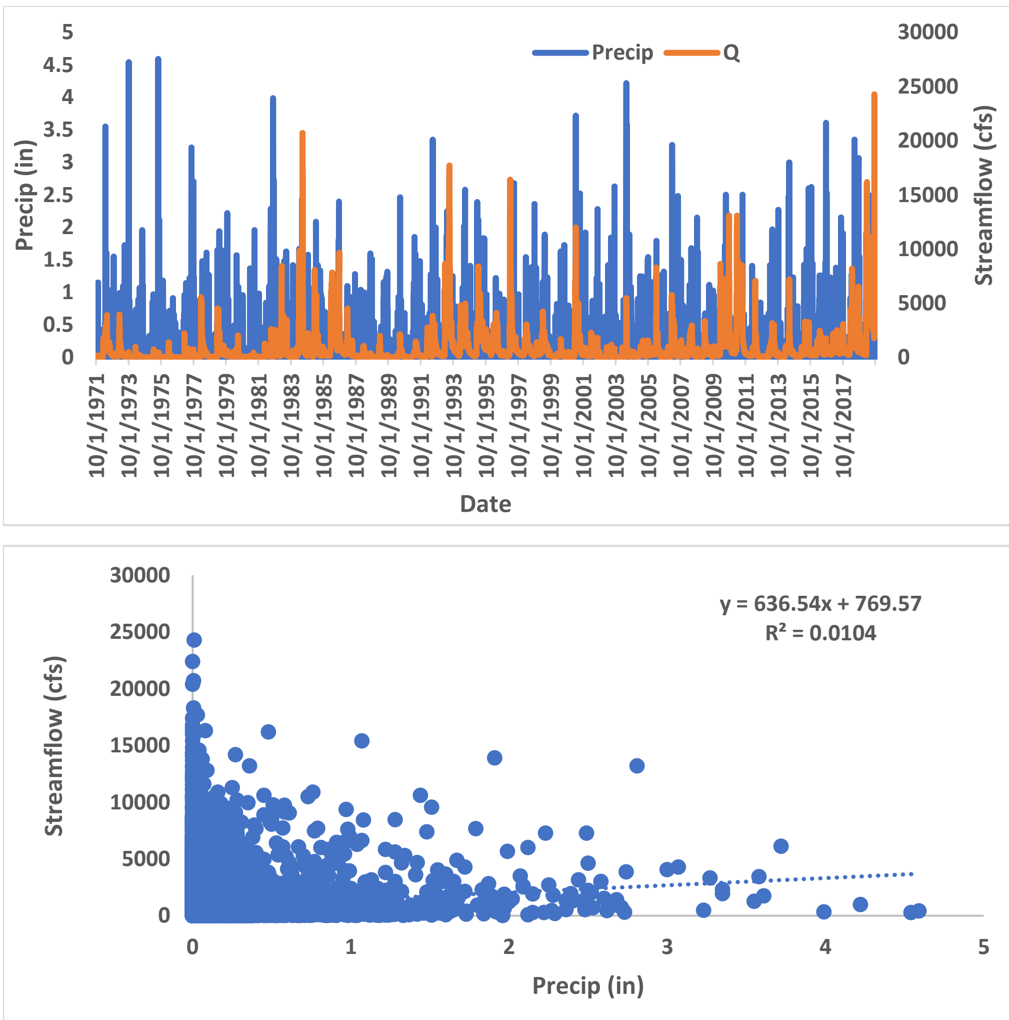


Figure 4.4. Daily average streamflow and daily total precipitation correlation for Big Sioux River at North Cliff Avenue from 1972-2019 water years.

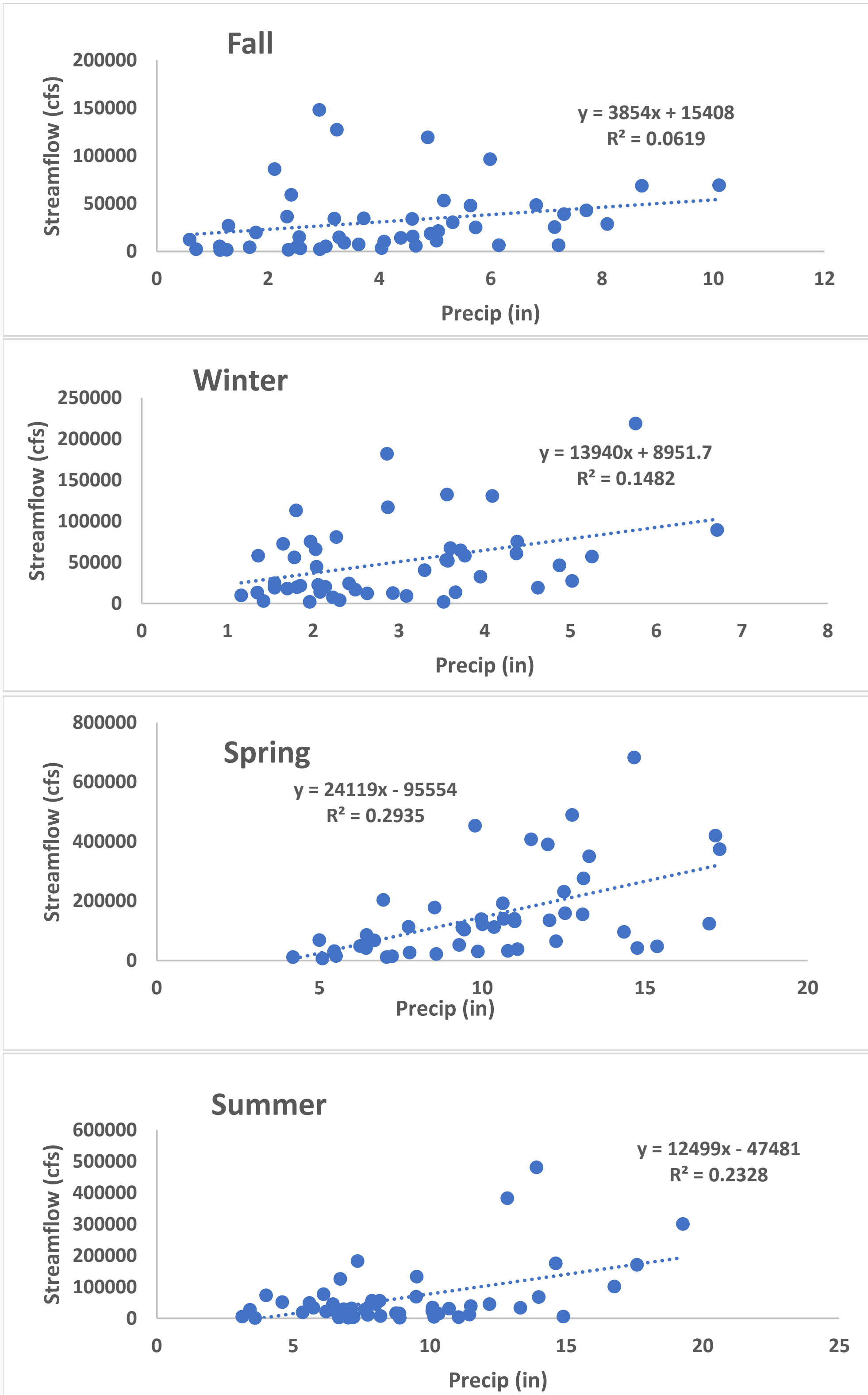
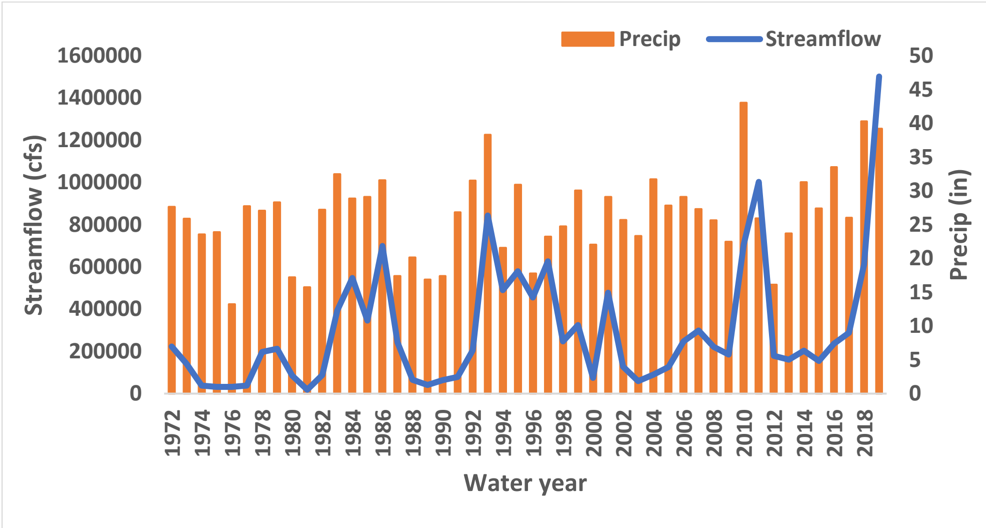


Figure 4.5. Correlation between accumulated seasonal streamflow and precipitation for Big Sioux River at North Cliff Avenue gauge from 1972-2019.

The results agree with (Ruppert, 2019) who found high seasonal correlation in Spring and Summer at Big Sioux River near Brookings. Seasonal correlation results also corresponds to the peak flows and floods events that occur in the Spring and Summer (Table 4.8). However, the results do not agree with (Towler et al., 2010) who found strong linear relationship between precipitation and streamflow for Winter months indicating rainfall runoff mechanisms for streamflow. The differences could be due to differences in climate and watershed characteristics, the precipitation falls as snowfall in Winter months in Sioux Falls.

The annual streamflow and precipitation for Big Sioux River at North Cliff Avenue from 1972-2019 ranged from 18,409 cfs in 1981 to 1,501,657cfs in 2019 with an average of 272,512 cfs (Figure 4.6). The correlation between annual streamflow and annual precipitation is 0.57, which indicates moderate correlation between the two parameters, with R squared of 0.32. The annual correlation is stronger than daily and seasonal correlation. This shows that the lag time needed for streamflow improves correlation. This shows that there is a positive relationship between annual streamflow and annual precipitation, showing that precipitation influences runoff and therefore streamflow.



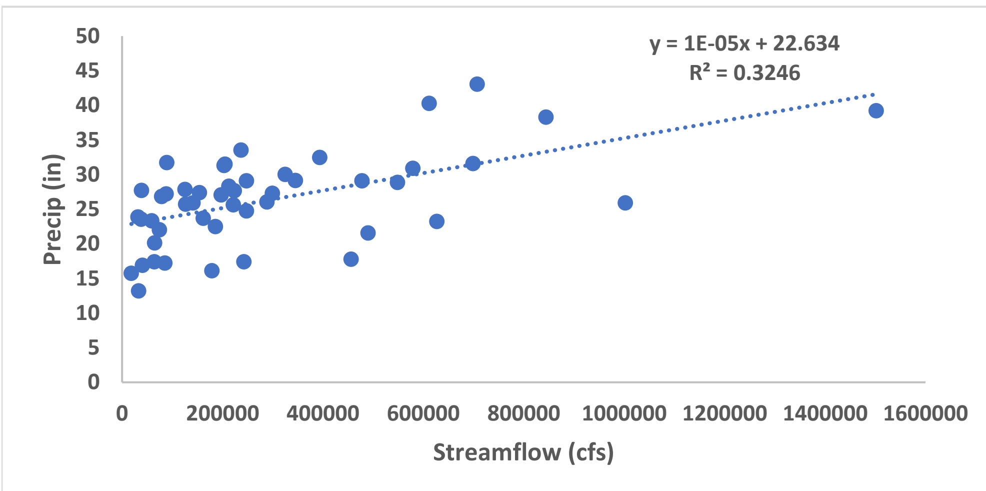


Figure 4.6. The accumulated annual streamflow and precipitation and their correlation for Big Sioux River at North Cliff Avenue gauge from 1972-2019.

Comparison of correlation with other gauges in Table 4.5 shows that daily streamflow and precipitation do not have correlation or have very poor correlation even though Big Sioux River at Sioux Falls shows a higher correlation (0.18) than other gauges. This is because the lag is required after precipitation to produce streamflow, therefore the increase in precipitation over longer period would increase the soil

moisture, ground water levels, and more runoff would occur as precipitation events occur. Thus, streamflow would occur steadily due to high ground water levels which will contribute to streamflow as baseflow. Therefore, the higher the correlation would be between precipitation and streamflow. The annual correlation, however, show that Big Sioux River at North Cliff Avenue gauge has highest correlation with 0.57 followed by Big Sioux River at Sioux Falls with 0.56 and Skunk Creek at Sioux Falls with 0.49. There was no streamflow data for Big Sioux River Below Diversion which is the stream gauge closest to the precipitation gauge (Figure 4.2). The difference in correlation is due to differences in ground water levels in each area and runoff. The Big Sioux River at North Cliff which has highest correlation is closer to precipitation gauge (2 miles) and it is the outlet of all streamflow in the watershed. The Big Sioux River at Sioux Falls also has higher correlation than Skunk Creek even though it is more distant from the precipitation gauge (5.2 miles) than Skunk Creek (3.5 miles).

Table 4.5. Streamflow and precipitation correlation comparison of gauge stations in the Big Sioux River in Sioux Falls.

		Daily		**Annual**	
Station	**Data range Used**	**Correlation**	**R^2**	**Correlation**	**R^2**
Skunk Cr	2003-2019	0.13	0.0165	0.49	0.24
BSR at Sioux Falls	2004-2019	0.18	0.033	0.56	0.31
BSR North Cliff	1971-2019	0.1	0.01	0.57	0.32

This is because Big Sioux River at Sioux Falls gauge is in the Big Sioux River watershed unlike Skunk Creek gauge which is on the Skunk Creek watershed which joins the Big Sioux River from west, and the gauge is located before Skunk Creek joins the Big

Sioux River. Spatial variability in precipitation influences the areas' variation in the amount of ground water which affects streamflow. The results could also be affected by the different ranges of datasets used (Table 4.5).

Generally, the possible reasons for streamflow and precipitation relationship in these gauges could be due to the watershed hydrologic response, which is influenced by factors such as watershed characteristics, infiltration, temperature, land use types, soil type, soil moisture, evapotranspiration, landscapes, precipitation magnitude, intensity and duration, runoff, groundwater levels, and the human activities such as such land use changes, pumping of water for irrigation, hydropower, industrial, agricultural, domestic, recreational uses (Guo et al., 2008; Miao et al., 2011; Riggs, 1985; Singh, 1997). Also, precipitation vary within a short distance and since the precipitation gauge in this station is located at the airport a little distant from the stream gauges (Table 4.2), it could affect the correlation. However, all precipitation in the watershed including upstream eventually drains to the outlet.

4.3.2. Flood Analysis

Figure 4.7 shows annual peak flows and the gauge height and flood stage for Big Sioux River at Northcliff Avenue. The peak flow ranged from 896 cfs in 1981 with gauge height of 8.13 ft to 40700 cfs in 1969 with gauge height of 27.45 ft meaning the peak flow of 1969 is historical and 2019 follows with high peak flow and gauge height. The average peak flow is 6365.13 cfs and gauge height is 15.15 ft. The peak flow corresponds with the gauge height as peak flow increase with increase in gauge height and peak flow decrease with gauge height. Table 4.6 shows the stage categories and total number of peak flow events in each category for Big Sioux River North Cliff Avenue.

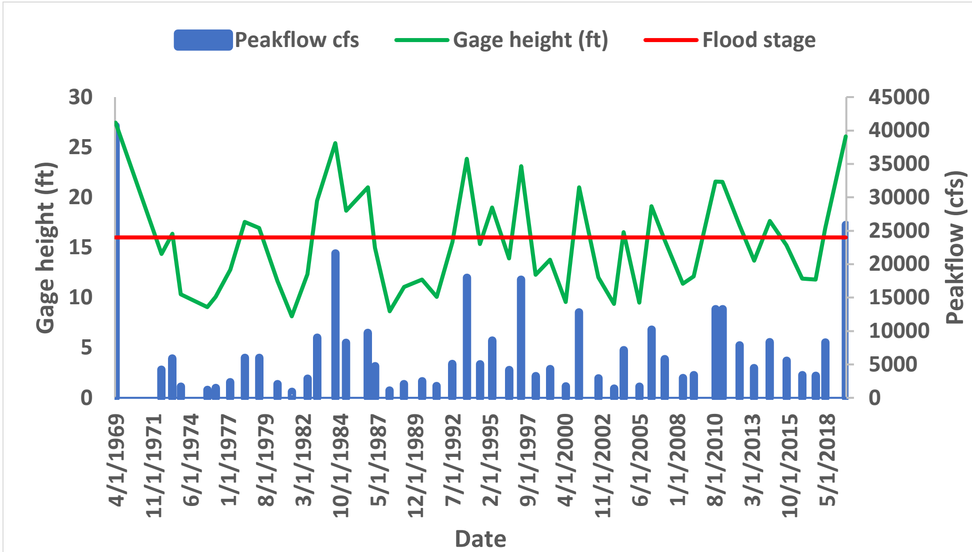


Figure 4.7. Gauge height, peak flow, and flood line for Big Sioux River at North Cliff Avenue (1969-2019).

The total number of floods at this gauge is 20 with gauge level from 16 ft and above, of which 7 are minor floods and 13 are moderate floods and there are no major floods that occurred at this gauge during the period of recording (1969-2019). The number of events when the gauge height is at 14 ft, which is action stage, is 6 years. This shows that the level of streamflow was almost at the level of flooding even though flooding did not yet occur.

Table 4.6. Gauge height range and total number of events in each stage category for Big Sioux River North Cliff Avenue gauge as identified in Figure 4.7.

Gauge height	Gauge stage	Total Events
14-16	Action	6
16-18	Minor flood	7
18-31	Moderate food	13
31 and above	Major flood	0

Table 4.7. Peak flow events, their climate category as identified in Chapter 2, and precipitation of prior and current season and their comparison to average seasonal precipitation for each event in each stage category for Big Sioux River North Cliff Avenue gauge (1969-2019).

Action (6)			**Seasonal Precip (in)**		
Date	**Peak flow (cfs)**	**Climate**	**Prior**	**Current**	**Level from average**
6/4/1972	4240	Average	1.6	12.1	below/above
3/25/1987	4770	Very Dry	2.2	3.7	below/above
7/1/1992	5080	Wet	6.3	16.8	below/above
6/27/1994	5050	Dry	1.8	10.6	below/above
3/18/2007	5810	Average	3.3	6.7	below/above
8/28/2015	5550	Average	9.3	14	below/above
Minor floods (7)					
Date	**Peak flow cfs**	**Climate**	**Prior**	**Current**	**Average**
3/13/1973	5880	Average	4.9	4.4	above
3/24/1978	6020	Average	5	1.4	above/below
3/23/1979	5990	Average	1.1	5	below/above
5/30/2004	7140	Wet	3.7	15.4	above
5/9/2012	7850	Very Dry	4.1	7.8	above/below
6/17/2014	8350	Wet	1.7	17	below/above
4/28/2018	8310	Very Wet	3.7	13.2	above
Moderate floods (13)					
Date	**Peak flow cfs**	**Climate**	**Prior**	**Current**	**Average**
4/10/1969	40700	Wet	5.4	7.5	above/below
3/7/1983	9000	Wet	10.1	4.1	above
6/22/1984	21600	Wet	3.3	17.2	above
3/22/1985	8230	Wet	5.2	2.9	above
9/24/1986	9730	Wet	11.5	14.6	above
7/7/1993	18000	Very wet	17.3	12.3	above
4/19/1995	8580	Wet	4.4	13.3	above
4/7/1997	17700	Average	2	9.8	below
4/23/2001	12800	Wet	2.9	12	above
4/8/2006	10200	Wet	3.6	11	above
9/27/2010	13300	Very Wet	12.6	19.3	above
3/25/2011	13300	Average	2.9	2.9	below/above
9/14/2019	25900	Very Wet	14.8	14	above

Table 4.7 shows the peak flow events and flow amounts, climate classification for that year of the peak flow event and precipitation for previous and current season and their level from average. The peak flow for minor floods ranged from 5880 cfs to 8350 cfs, while moderate floods ranged from 9000 cfs to 40,700 cfs. The flow at action stage ranges from 4240 cfs to 5810 cfs. The peak flow events at action fall in Average, Wet and Very Dry climate and the seasonal precipitation was below average for previous season and above average for the season of the event. This shows that more precipitation was in the season of the event. The minor floods events show that the 1970s fall in Average climate and the 2000s fall in Wet and Very Wet climate. Some minor flood events seasonal precipitation for preceding and current season of the event are above average and some are above average in preceding season and below average current season of the event while some have below average preceding season and above average current season of the event. This shows that floods could be influence by precipitation of the past seasons and the current season and event in dry climate, floods and high peak flows still occur due to seasonal precipitation.

The moderate flood events fall in Wet and Very Wet climate except 1997 and 2011 which fall in average climate. All precipitation of previous and current season of the event in Wet and Very Wet climate are above average except in 1969. 1969 had prior season above average. The flood events in 1997 show that seasonal precipitation was a below average for both previous and current season of the event, however, seasonal precipitation before those two (Fall) was higher than average therefore that contributed to the peak and flooding. The 2011 event had previous season below average and current

above average and the preceding year had high precipitation in the Summer and therefore the high ground water levels contributed to the peak flow in the Winter in 2011.

Although most of the flood events are in Very Wet and Wet climate classifications, some floods events fall in Average and Very Dry climates, indicating that floods were due to the snowmelt as the events occurred in March to May. The peak flow events in Very Wet climate classification are mainly due to liquid precipitation and the years had high precipitation during those months of peak flows. Therefore, the peak flow is due to both liquid precipitation and snowfall.

In comparison with other stream gauges in Big Sioux River, Table 4.4 shows the stream gauges and their gauge heights limit in each stage category including flood categories. The Big Sioux River at North Cliff Avenue has highest stages for flood limits (16 ft to 31 ft) and Big Sioux River at Sioux Falls has lowest stage for flood limits (8 ft for minor floods to 14 ft for major floods). Table 4.8 shows comparison of flood events at each gauge.

The peak flow and gauge height at the Big Sioux River below diversion from 2003 to 2019 ranged from 100 cfs in 2008 to 2000 cfs in 2019 and gauge height ranged from 4.71 to 9.2 ft in the same years, respectively. The averages are 547.4 cfs and 6 ft . Flood stage is 15 ft at this gauge and no floods occurred at this gauge station (Table 4.8), meaning the peak flow events are below flood stage. This is due to the diversion canal that diverts streamflow, thus reducing flooding at the airport where the stream gauge is located. Peak flow and gauge height at Big Sioux River at Sioux Falls from 1944 to 2019 ranged from 493 cfs in 1958 to 16200 cfs in 1957 and gauge height ranged from 3.49 ft in

Table 4.8. Stream gauges and their number of events and total number of floods in each stage category in Big Sioux River in Sioux Falls.

Number of events for each category					
Gauge	Action	Minor	Moderate	Major	Total Floods
BSR North Cliff	6	7	13	0	20
BSR Below Diversion	0	0	0	0	0
BSR at Sioux Falls	5	18	5	4	27
Skunk Cr	10	10	1	2	13

1957 to 16.9 ft in 2019. The averages are 4851.8 cfs and 9.8 ft. The total number of floods in this location is 27 of which 18 were minor, 5 were moderate, and 4 were major floods while 5 were action stage. Skunk Creek peak flow and gauge height from 1949 to 2019 ranged from 43 cfs in 1981 to 29,400 cfs in 1957 and 2.87 ft in 1981 to 18.23 ft in 2019. The averages are 3017.8 cfs and 7.8 ft. The total number of floods are 13, of which 10 are minor, 1 is moderate and 2 are major floods.

The results show that a lot of floods occur in Sioux Falls and the Big Sioux River watershed at Sioux Falls experiences more flooding than other gauges and even though most are minor and moderate, major floods also occur. Skunk Creek also has more minor floods but still experiences moderate and major floods. This shows that each gauge is different, and the spatial precipitation variability and each area’s ground water levels contribute to the differences. This shows that flood studies are important part of climate variability because precipitation cause floods and floods still occur even in the Very Dry climates. Therefore, it is important to gain an in-depth understanding of floods

occurrences and how to reduce their risks. The climate variability and extremes, and land use change due to urbanization play a major factor in increasing runoff and peak flows resulting in flooding. The dominant soils in Big Sioux River watershed at Sioux Falls is Group C (sandy clay loam), and D (clay loam, silty clay loam, sandy clay, silty clay or clay) (USDA, 2021). These soil groups have highest runoff potential and very low infiltration rates when thoroughly wetted and consists chiefly of clay soils with high swelling potential, soils with a high permanent water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material. This indicates that the potential for flooding is very high in this watershed. More in-depth precipitation and streamflow relationship and flood analysis that include watershed characteristics is needed to gain an in-depth of flood risks.

4.4. Conclusions

The long-term streamflow and precipitation relationship, peak flows and floods events were analyzed for stream gauges in the Big Sioux River at Sioux Falls.

- The results show poor or no correlation between daily streamflow and precipitation due to lag required for continuous precipitation to increase ground water levels for streamflow to occur. The Big Sioux River at North Cliff Avenue show moderate correlation in the Spring and Summer and weak correlation in Winter and poor or no correlation in the Fall. Annual correlation is higher than daily and seasonal correlation. Annual show moderate to weak correlation for all stream gauges.
- Big Sioux River at North Cliff Avenue has higher correlation (0.59) between precipitation and streamflow, followed by Big Sioux River at Sioux Falls (0.56)

and Skunk Creek with 0.49. There was no streamflow data for Big Sioux Below Diversion. The correlations show that gauges at Big Sioux River (same drainage area) have better correlation than Skunk Creek (different drainage area) due to spatial variability. The Streamflow is recorded as daily mean and precipitation is the daily sum, this could affect the accuracy of results.

- Big Sioux River at Sioux Falls has many flood events than other gauges (27) which are minor, moderate, and major. The Big Sioux River at North Cliff Avenue, which is the outlet of the watershed also has many floods events (20) which are minor and moderate but no major. Skunk Creek also has minor, moderate and major floods with total of 13 floods. The areas around these gauges are in major risk of flood damages.
- Climate is highly variable in the study area indicating less predictability, even in Very Dry climate, floods still occur. The less predictability would affect the forecasting, planning and management of water resources and the agriculture which is mainly dependent on rain would be affected. Floods events in March to May could be mainly due to snowmelt and in the summer months due to liquid precipitation.

The findings presented here would be very beneficial for future research, and water resources management including floods mitigations and planning. The results should be considered in floods, drought, climate, and water management decision making.

Chapter 5: Summary and Conclusions

The study analyzed and quantified precipitation variability, extremes, precipitation and streamflow relationship, and floods events for Sioux Falls.

Chapter two: Precipitation variability was quantified for 1895-2019 period of record for cumulative variability and for climate classifications.

2010 has highest precipitation (43.1 in) and 1976 has lowest precipitation (13.1 in). The trend shows that in general, about 0.0092 in is added annually meaning precipitation is increasing linearly. The Very Wet climate and Wet climate are higher than average climate by 48% (12.5 in) and 21% (5.3 in) respectively while Very Dry and Dry climates are lower than average climate by 36% (9.2 in) and 19% (4.8 in) respectively. The highest seasonal precipitation is in the Summer (19.3 in) in 2010 and lowest was in the Winter (0.4 in) in 1901. However, on average, precipitation is highest in the Spring followed by Summer.

June has highest monthly precipitation with 13.7 in. in 2014, a 9.5 in increase from average. Generally, January has lowest precipitation and June has the highest. The CVs show that June is less variable, and November is highly variable month. Generally, months, seasons and years with high precipitation have less variable precipitation and the ones with less precipitation have highly variable precipitation from the mean. Very Wet climate has highest precipitation in July while Wet, Average, Dry, and Very Dry have highest in June.

Precipitation is highly variable in the study area, indicating a less predictable climate and a challenge for reliable water resources and a challenge for rainfed agriculture which is a

common practice in the study area. This makes early preparation for extremes such as floods and drought a challenge as forecasting needs to be done early before extremes occur.

Chapter three: The inter and intra annual, seasonal, and monthly precipitation and snowfall variability, and their number of days for Very Wet and Very Dry climates from 1895 to 2019 were analyzed to quantify variability and identify any patterns or their absence. The results show inter and intra annual, seasonal, and monthly precipitation and snowfall variability. Very Wet show an increase of up to 70% (2010) in annual precipitation from long-term average and snowfall increase of up to 116% (1962). Very Dry climate show an annual precipitation decrease of up to 49% (1976) and snowfall decrease of up to 73% (1987). Very Wet has highest precipitation in the Summer and Very Dry has highest in Spring and both have lowest in Winter. Winter has highest snowfall and Spring has lowest. Very Wet has highest precipitation in July and Very Dry has highest in June and both have lowest in January. Snowfall amounts do not correspond with precipitation amounts; some years have high precipitation and low snowfall and vice versa. The number of days with precipitation and snowfall do not correspond with the precipitation and snowfall amounts, the intensity influences the totals.

Chapter four: The correlation between streamflow and precipitation and flood events were analyzed for gauges in the Big Sioux River drainage area in Sioux Falls.

The results show no daily correlation between streamflow and precipitation for all the gauges due to lag required to produce streamflow. Seasonal correlation at Big Sioux River at North Cliff Avenue gauge show that Spring has moderate correlation followed by Summer while Winter shows a weak correlation and Fall show very poor or no

correlation. Annual correlation is higher than of seasonal meaning the lag time improves correlation. Big Sioux River at North Cliff Avenue has higher correlation (0.59) followed by Big Sioux River at Sioux Falls (0.56) and Skunk Creek with 0.49. There was no streamflow data for Big Sioux River Below Diversion, which is closest to the precipitation gauge. This shows that gauges at Big Sioux River with same drainage area with precipitation gauge had better correlation than Skunk Creek which is another drainage area. The Big Sioux River at Sioux Falls has 27 flood events which are minor, moderate, and major. The Big Sioux River at North Cliff Avenue, which is the outlet of the watershed also has high floods events (20) which are minor and moderate. Skunk Creek also has minor, moderate and major floods with total of 13 floods. The areas around these gauges are in major risk of flood damages indicating the need to reduce flood risks. Floods events in March to May are due to snowmelt and in the Summer months (June to September) are due to rainfall. The results also indicate that even in Very Dry climate, there are flood events due to high precipitation and snowfall events, and the accumulation of streamflow from the previous year and seasons as they contribute to the increase in the level of groundwater.

The findings provided here prove non-stationarity and show that climate variability and extremes at local scale are more important than at regional scale and should be incorporated in planning and management of water resources and climate including floods and drought mitigations. Designs of infrastructure from local precipitation is important than design from regional data to avoid underestimation or overestimations. The findings here also provide support for further investigations in water and climate research.

Chapter 6: Recommendations and Future Work

The study analyzed and quantified precipitation variability, precipitation and streamflow relationship and extremes.

6.1. Limitation of the Study:

The following were found to be limitations in this research:

- Due to missing data and short period of record in some stations, only one precipitation gauge was used that had long consistent data and some gauges had short period of record or inconsistent data as they were installed later. This creates a limitation as only one gauge's precipitation data is assumed to represent the study area.
- Inconsistent data sets. Streamflow data was shorter than precipitation data, therefore, shorter period of data was used for consistency in analyzing precipitation and streamflow correlation. Some stations had gaps missing streamflow data, only the portion with consistent continuous data of more than 10 years was used not the full period of record. The Streamflow is recorded as daily mean and precipitation is the daily sum, this could also affect the accuracy of results.

6.2. Recommendations:

- This study found that precipitation increase is due to precipitation magnitude not frequency of precipitation, analysis of the intensity of precipitation could provide insights on the increase in precipitation intensity and extremes.

- The runoff from snowfall and rainfall should be investigated to assess how much of streamflow and floods results from snowmelt and how much results from rainfall and this will aid in planning and management.

- Analysis of watershed factors affecting streamflow will provide important insights on the causes of floods and drought.
- This study performed monthly, seasonal, and annual analysis of precipitation variability. Use of peak over threshold (which choses a threshold) and annual maxima (which identifies maximum value for each year) for analysis of daily precipitation extremes could be performed to compare the local scale precipitation with IDF curves which are derived from regional precipitation data, for local scale designs.

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